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Informal Report

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**Benefit/Cost Analysis for Research in
Geothermal Log Interpretation
Final Report**

University of California

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LOS ALAMOS SCIENTIFIC LABORATORY

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Benefit/Cost Analysis for Research in Geothermal Log Interpretation Final Report

**Prepared for
Los Alamos Scientific Laboratory**

by

**F. A. Rigby*
P. Reardon***

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BENEFIT/COST ANALYSIS FOR RESEARCH IN GEOTHERMAL LOG INTERPRETATION

Final Report

by

F. A. Rigby and P. Reardon

ABSTRACT

Well log interpretation, the process of inferring subsurface geology from geophysical measurements made in boreholes, is the most versatile and direct means available of assessing important physical and structural reservoir properties. Historically, well logging has been developed primarily for use in oil and gas wells, and its application in a different environment such as a geothermal reservoir creates complex problems. Present geothermal development is severely hindered by lack of data. Adaptation of well logging techniques holds the promise of reducing development costs, encouraging investment, and assisting regulatory permitting. Such benefits will translate directly into lower power costs and an increased domestic energy supply. A significant acceleration of geothermal power-on-line is possible plus cost reductions through reduction of drilling failure rate, reduction of average well cost, earlier recognition of bad wells, reduced flow testing, and savings due to provision of better data for regulatory decisions. Net undiscounted benefits in 1979 dollars from improving logging and interpretation in geothermal areas can exceed half a billion dollars in slightly more than a decade, about 300 million of this should be regarded as the potential benefit of the Los Alamos Scientific Laboratory Geothermal Log Interpretation Program or similar research.

The development of the geothermal resources of the United States provides an energy source which can materially reduce our dependence on foreign fuel supplies and benefit the economy. With each blow dealt by world events to the international oil market, we become more aware that we may soon face a time when we shall have to place far greater dependence on domestic energy sources than is now the case. As the time approaches, it becomes important to ask whether we have available the tools and technology needed to rapidly expand our use of unconventional energy sources. Geothermal energy is relatively benign environmentally and can in many cases be brought on-line with a shorter lead time than nuclear or coal-fired power plants, making geothermal energy a good candidate for rapid development.

Development of geothermal power plants is paced by a number of factors of which the most important are, obviously, the rate of discovery of resources and the cost relative to competing energy supplies. The cost of geothermal energy is significantly affected by the risk and cost involved in drilling and developing a geothermal field. Other factors affecting development include the willingness of investors to commit capital to geothermal energy and regulatory restraints which may be necessary to protect the environment or to ensure orderly and equitable development. Many of the problems of development stem from the fact that one is dealing with subsurface conditions of which we have only limited knowledge. Similarly both the confidence of investors and the deliberations of regulatory agencies are significantly affected by the limited knowledge that we have of the long-term performance of geothermal resources. One way of encouraging the development of geothermal energy is to provide better means of obtaining data on the resources that we seek to use.

1.1 GEOTHERMAL WELL LOGGING

The most versatile means of obtaining data from below the earth's surface is by lowering logging instruments, which measure a variety of physical and sometimes chemical parameters, into a borehole. The data most commonly recorded on the well logs include temperature and pressure in the borehole and various physical properties of the surrounding rock including electrical characteristics, the velocity of sound, radioactivity, and the absorption and scattering of externally applied radiation such as neutrons and gamma rays. By applying a variety of relationships developed from analysis of the response of the logging tools in known or simplified theoretical borehole conditions, the unknown conditions in the logged well are inferred (Schlumberger, 1972). Because tool response can be sensitive to numerous downhole conditions, simplifying assumptions are necessary in any theoretical model of response, and a high value is placed on practical experience under known conditions. Parameters such as the depth, thickness, and permeability of resource zones are sought to guide development and aid in assessing the potential of a resource.

The collection and interpretation of well log data has developed to date largely in response to the needs of the oil and gas industry, with some contributions from mining and hydrology. Well logging has played a vital role in the development of the modern petroleum industry. Most of the techniques for the interpretation of logged data have been developed empirically for the formations in which hydrocarbons have been commonly sought. The conditions, important parameters, and geology of geothermal reservoirs can be radically different from those involved in petroleum exploration, however. At present geothermal development is able to gain only very limited advantage from well logging.

Geothermal resources are found in areas where the great heat of the interior of the earth has been brought closer than normal to the surface. Thus, the geology of geothermal areas tends to be complex. The types of rock encountered are often different and more varied than has been common in oil and gas development. Often the response of the logging tools to such rock is not known. Temperature is another complication; many geothermal wells are too hot to be logged with presently available tools. Also, the knowledge that we need to deal with a geothermal reservoir is not the same as is desired to assess an oil or gas well.

Well logging for the petroleum industry first developed in the 1920's and 1930's (Schlumberger, et al., 1934; Alluad and Martin, 1977) when there was a sufficient demand for logging services to stimulate industry. Logging techniques have developed slowly over a period of decades. Today, because geothermal development has barely begun, there is little demand or market to stimulate the development of specialized geothermal logging services. However, by developing the knowledge necessary to interpret the characteristics of geothermal reservoirs from log data, geothermal development can be accelerated.

1.2 SUMMARY

This report presents the results of the analysis of the benefits and costs of improved wireline logging in geothermal boreholes. This analysis was prepared for the Los Alamos Scientific Laboratory (LASL) Geothermal Log Interpretation Program (GLIP). Presented in this report are the findings regarding the net benefits that may be realized as a result of improved log interpretation in geothermal wells, allowing for the probable costs of obtaining this information. Benefits are

organized into several major benefit types, each of which will contribute their own priorities and research demands to the GLIP, and conclusions that can be drawn from the economic analysis regarding possible research priorities or program approaches are discussed. The projected benefits are discounted for present value for purposes of comparison with other programs and estimation of funding levels that might be justified for the accomplishment of the indicated research. (Appendix D contains a discussion of the concept of discounting future benefits for present value).

The estimation of net total benefits for improved geothermal logging techniques was made for the near-term only (power-on-line through 1992). Although significant additional benefits will accrue in the longer term, projection of the probable long-term expansion of geothermal development was beyond the scope of this study. Similarly, benefits were quantified only for hydrothermal resource areas since extensive near-term development of hot dry rock is uncertain (geopressured resources are sufficiently low in temperature and similar in lithology to oil and gas formations to have only a limited requirement for new log interpretation techniques).

Improvements in the process of geothermal development can come about in three ways. 1) A direct reduction in the costs associated with development will produce a benefit equal to the dollars saved. This benefit may ultimately be realized as a reduction of the cost of power or as increased investment in development elsewhere, which will yield benefits indirectly. 2) A reduction in the risk of development will produce benefits of two types; lower risk effectively reduces the cost of development since less loss is encountered in unsuccessful investment, and development may be accelerated by increased availability of investor capital in response to the reduced risk. 3) Improved data that can aid the process of applying for and obtaining

regulatory permits can allow more rapid completion of proposed power plants. Figure 1-1 illustrates this analysis of the benefits to be gained from improved data on the resource.

Wherever possible, benefits were related directly to reduced costs and calculated as a savings to the developer. These savings are associated with the field development process and for the most part with reduction in either the cost of drilling or the number of wells required (e.g. a reduction in the percentage of dry holes reduces the total drilling requirement). These cost reductions were estimated and interpreted directly as a benefit.

Some benefits will not be associated with a net cost reduction, but will result in more rapid completion of power plants. Particularly significant is the possibility that less time need be spent assessing a resource before power plant construction is initiated. Assessing this benefit in terms of a dollar value is not simple. In order to estimate the total national benefit that would accrue from a more rapid development of domestic geothermal energy supplies, the extra electricity that would be supplied by earlier geothermal plant completion was estimated in terms of the equivalent volume of oil that would be required to provide an equal amount of electrical energy. This volume of oil is an incremental savings due to earlier power plant construction resulting from the availability of better resource data and should not be confused with the total oil displacement projected for geothermal development as a whole. To obtain a dollar value, the oil equivalent was multiplied by \$16 per barrel, a price commensurate with the delivered price of imported oil.

Based on conservative estimates of the possible improvements, the net near-term benefits to geothermal electric power generation from improved logging were estimated in constant 1979 dollars. The geothermal development scenario presented in

Figure 1-1. Nature of Benefits Expected From Improved Log Interpretation.

Prospects for Improvement in Geothermal Well Technology and Their Expected Benefits (MITRE, 1978) was designated as the basis of the analysis. This scenario provides hypothetical achievement of power-on-line and the associated drilling requirements in terms of well depths and well costs. Benefits were estimated based on projected drilling through 1990. Since production wells drilled in 1990 were assumed to be for power plants completed in 1992, power-on-line was considered through 1992.

Since some added expenditure will be required to achieve these benefits, an estimate was also made of the cost of extensive logging in the wells of the scenario. This was subtracted from the gross benefits to provide net benefits. Table 1-I shows the estimated net benefit stream and present value at various discount rates. Since these benefits result from both the existence of logging tools that can operate under geothermal conditions and appropriate data interpretation, the benefits were apportioned between tool development and log interpretation for those resources with temperatures too high for reliable operation of present logging tools.

The benefits displayed in Table 1-I necessarily embrace only those benefits that can be readily quantified. No allowance was made for benefits that could not be estimated within the context of the near-term electric power development. However, less easily estimated benefits will be nonetheless real and significant. Additional benefits will result from power-on-line development after 1992, improved reservoir management for longer reservoir life, logging in wells drilled for direct use application, and applications to hot dry rock and well stimulation programs. Thus the quantitative benefit estimate in Table 1-I represents a lower bound on the total benefits.

Since Federal research funds are limited, and since many implementation actions must intervene between the performance of research and the realization of benefits, it is usual to require

Table 1-I. Benefit Summary

Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
	Millions of Dollars (1979 Dollars)													
Benefits Related To Field Development Less Logging Costs	-0.7	-0.4	2.0	5.3	8.6	12.2	27.3	34.9	25.0	86.8	66.2	70.3		
Benefit From Accelerated Power-On-Line	0	0	0	0	2.8	0	9.1	8.3	14.4	17.5	12.1	40.1	29.5	30.8

<u>Discount Rate*</u>	<u>Total Present Value</u>	<u>Benefits Attributed to GLIP</u>
0%	502.1	310
5%	321.4	200
10%	212.5	130

*Benefits are in 1979 constant dollars; so, effect of inflation is removed. Thus, discount rate applies to real value and should not include allowance for inflation.

that research programs have a high ratio of expected benefits to costs. A benefit/cost ratio of 10 to 1 is not an uncommon criterion for evaluation of research programs. The GLIP was assumed to have an eight-year duration. Table 1-II summarizes the results of applying a 10 to 1 benefit/cost ratio to the estimated near-term benefits for hydrothermal electricity generation only.

TABLE 1-II. SUMMARY OF BENEFIT/COST RATIO
(MILLIONS OF 1979 DOLLARS)

<u>Discount Rate</u>	<u>Expected Value</u>	<u>Appropriate Cost at 10:1 Ratio</u>	<u>Appropriate Cost Per Year for 8 Years</u>
0%	310	31.0	3.9
5%	200	20.0	2.5
10%	130	13.0	1.6

1.3 POTENTIAL LEVERAGE OF FEDERAL RESEARCH PROGRAM

When any program of Federal expenditures for research is undertaken, one obvious question that should always be asked is "What is being done in the same field by industrial research operations?" The value of a Federal research program can be greatly increased if the Federal expenditures act as a trigger to start research activity in private industry. This is "leverage," the fact that one dollar spent on basic research may cause several dollars to be spent by non-governmental sources on applying and commercializing the products of the research. It is also desirable that Federal research funds to be directed toward fields in which private research is not already heavily engaged. If industry involvement is too great, the Federal funds may not add significantly to the research effort and thus will not achieve very much leverage. Federal research funding should be directed toward achieving results for which there will be a future need, but which might not be achieved in a timely fashion otherwise.

The position of the logging industry with regard to the interpretation of logging data for geothermal applications is complex. The supply of logging services for oil and gas, and thus also geothermal, wells is dominated by a relatively few large service companies. As remarked above, the techniques of well logging have been largely developed for the needs of the petroleum industry, and these requirements continue to control the industry's attention. For the last several years, petroleum drilling has been experiencing an almost explosive expansion. The rising cost of energy is supplying the capital to extend both exploration and production drilling to greater depths and into more difficult or less promising formations. As wells go deeper and become more expensive the footage to be logged increases, and these high cost wells also place pressure on the operators to obtain the maximum available data from each well; all of which creates a high demand for logging services.

The expansion of petroleum exploration has both positive and negative aspects from the point of view of logging in geothermal wells. A major positive feature is the development of hostile environment (high temperature) logging (HEL) tools. Even though the thermal gradients in areas explored for petroleum are generally far less than the gradients sought by the geothermal industry, the fact that oil and gas wells are now being drilled to six and seven kilometer depths means that temperatures of 150°C and more must be faced. Several HEL tools rated for temperatures around 200°C are now available, which has greatly benefitted geothermal logging. On the other hand, these tools still do not have the capability to log many geothermal reservoirs, and there is still considerable room for improvement in their performance.

The oil and gas industry is also being forced more and more into dealing with metamorphic and extensively altered sedimentary rocks and reservoirs in which permeability is dominated by fracturing rather than the intergranular porosity of the rock. Here again, these conditions overlap the concerns of geothermal development.

On the other hand, there are obvious divergences in the data required from logging and log interpretation between oil and gas drilling and geothermal drilling. The former is, and will remain, primarily interested in the identification of large volumes of hydrocarbons from the well logs; very little interest is likely to be attached to the location and analysis of high-temperature, high-permeability water-bearing formations. The tools that the logging industry gives highest priority for HEL development will not necessarily be those which will be of the most use to geothermal developers. For example, the petroleum industry is satisfied with relatively simple temperature data, since it is needed mainly for correcting changes in instrument response. The geothermal industry, however, has a strong demand for continuous, accurate formation temperature logs. The same will be true of the techniques of interpretation. While the expansion of the search for oil and gas is leading to interest in formations that share some characteristics common in geothermal reservoirs, some of the most important interpretation problems in geothermal reservoirs are not of great importance to oil and gas development. A large proportion of geothermal reservoirs, for example, occur in fractured volcanic formations - not a good candidate formation for the search for hydrocarbons.

Logging of geothermal wells is perceived by the logging industry as being only a very small area of business. Approximately 50,000 new oil and gas wells are drilled annually in the United States. With both the number and depth of wells increasing, the logging service industry sees ample opportunities for growth in the oil and gas service areas, a perception that is reinforced by the opinion that logging is currently underutilized in many operations and that the market can be significantly expanded. Geothermal drilling at present accounts for less than 100 wells per year, and even the most optimistic estimates place it at no more than a few percent of total U.S. drilling activity for the next decade and more. Thus, while there is no impulse on the part of the logging service industry

to ignore the needs of the geothermal industry, development of log interpretation techniques to deal with geothermal reservoirs will not receive much priority.

An excellent example of this situation is provided by the problem of calibration. Experience is already sufficient to show that in hot igneous formations (and in some other geological formations) that are often encountered in geothermal logging, the response of the logging tools is outside the range of calibration normally used by the logging industry. In the case of tools with non-linear response or interpretation techniques that depend on empirical formulas, this presents a severe problem. Because of the limited market represented by geothermal logging, the industry is not prepared to make the investment to provide calibration facilities. The GLIP program can fill the gap by making available designated geothermal wells and establishing calibration pits with known structure for tool calibration. The industry has shown itself to be ready to take advantage of such facilities, once they are provided, to test and calibrate their HEL (high temperature) tools.

The requirement for a federal research program is therefore clear. Improvement in our ability to find and analyze geothermal reservoirs from well logs can significantly benefit the development of geothermal energy in the U.S., and research support will be required to provide the necessary techniques. Without such support, industry research will not be directed at solving problems related to geothermal log interpretation. On the other hand, the logging service industry will not ignore the results of GLIP research. As has already been pointed out, the oil and gas industry is increasingly encountering problems that are similar to those of geothermal logging.

The present demand for expanded logging services in the petroleum industry is thus a mixed blessing for geothermal logging. The HEL tools being developed by the logging service

industry can be used in many, but not all geothermal reservoirs. But these tools are not necessarily those which would be most useful in geothermal applications. Similarly, even if tools are available, the industry is not yet concentrating on solving the interpretation problems that must be faced to work with the kinds of lithologies found in geothermal reservoirs. On the other hand, if the GLIP program develops new interpretation techniques, the industry will be quick to apply and commercialize them for use in oil and gas exploration in complex formations. The Geothermal Log Interpretation Program therefore fills an essential role in initiating research on the needs of geothermal development which will otherwise be neglected. At the same time, at least some aspects of the GLIP will enjoy considerable leverage in terms of technology transfer and commercialization.

2.0 IDENTIFICATION OF BENEFITS

2.1 CHARACTERISTICS OF GEOTHERMAL DEVELOPMENT

The types of benefits that can be achieved for geothermal development are directly related to the nature of the undertaking. Since the geothermal industry deals with the discovery and development of subsurface resources, the availability and quality of resource information plays a major role. As already noted, better resource data which might be supplied by improved logging and interpretation in geothermal wells will produce benefits of three types: 1) development cost reduction, 2) risk reduction, and 3) benefits in the permitting process. All of these benefits occur in the early stages of geothermal operations, which gives them added significance.

Geothermal development is extremely capital intensive. Large initial investments are made and repaid over the long-term; operating costs are a relatively small factor in the total cost of geothermal power. Initial capital costs and risks are therefore of great importance.

The investment required for geothermal development can be divided between field development and power plant construction. In some cases both efforts are being undertaken by a single developer, but it appears that a more typical pattern will involve a field developer and an electric utility. Even in those cases in which the field developer is also constructing the power plant, the electricity will be sold to a utility, so that some involvement of a utility will occur.

Data from well logging provide information regarding the geothermal field. While some contributions to plant design appear possible, the bulk of the direct cost reductions that may be achieved with log data will involve field development. Highly

significant gains in terms of the acceleration of power-on-line can be achieved in terms of the effect on the utility involvement.

Electrical utilities are operated as regulated monopolies. As such, their investment structure is oriented toward low capital risk. One of the two most significant factors controlling the rate of development at a geothermal resource is willingness of utilities and other investors to make commitments to geothermal plants (the other factor is the relative cost of competing energy supplies). The chief uncertainties that contribute to the risks involved lie in the limited data that can be gathered regarding the character of the geothermal resource prior to large-scale development. Better logging data will directly affect this problem. Geothermal development can also be accelerated by improved environmental protection. Following the decision to develop a geothermal area, regulatory processes become a significant factor. Better data on the reservoir can speed the permit granting process. It may also allow reductions in certain development costs.

Benefits of two types have thus been included in this study. First, savings related to field development have been estimated in terms of the drilling scenario through 1990. Some of these savings are directly related to the cost of drilling; others, however, follow from improvements in such operations as well siting, field testing, and reinjection requirements. Second, benefits relating to the accelerated achievement of power-on-line have been estimated. These benefits may result from less time required to test a field prior to the commitment to proceed with development, fewer wells required to locate and test a plant site, faster permitting, or other simplifications in field development.

2.2 PHASES OF DEVELOPMENT

Geothermal development can be divided into seven overlapping phases:

- o exploration
- o assessment of value
- o reservoir modeling
- o production drilling
- o plant design and construction
- o environmental protection
- o reservoir management and operation

While these steps are semi-sequential, they also may overlap both in time and in the sense that the dividing line between one phase and another will always be somewhat arbitrary. For example the process followed by a field developer in exploring a potential resource will vary depending on local conditions and the degree of success achieved. The transition from exploratory to production drilling will always be to some extent a fiction since each new well will add something to our knowledge of the reservoir, but the fact that the separation between phases is sometimes difficult to define does not reduce the usefulness of considering development in these terms. The inclusion of "reservoir modeling" as a separate phase is useful in terms of analyzing the potential benefits of improved log interpretation. The extent to which a given developer will attempt to prepare a model may vary from a simple conceptual picture to detailed numerical simulation. The purpose of modeling is to serve the other phases, particularly assessment of value, but also the drilling program, plant design, environmental protection, and long term reservoir management. Because the data derived from improved log interpretation can have enormous impact on the quality of reservoir modeling, it is useful to isolate it as a separate phase.

The most obvious contributions of well logging are to exploration, assessment of value, and modeling. However, the planning of a drilling program may also be significantly aided with a better understanding of subsurface conditions. The contributions that well logging can make to plant design are considerably more limited and hard to assess. Downhole chemical measurements, of which pH appears to be the most feasible and useful, may be of use in projecting corrosion and scaling problems, and of course conclusions regarding field life will affect plant design. Environmental protection and long-term reservoir management can also benefit. Well logs can be interpreted to provide data on reservoir structure and strength that could assist in assessing the hazards of subsidence. In addition logging will be very important in monitoring changes in the field during production. These benefits, however, are difficult to estimate quantitatively. They will occur in the long term and may affect some resource areas greatly and others not at all. In the estimates made in this study, benefits in plant design are regarded as small compared to other benefits. Benefits for improved reservoir management are long-term and fall outside the time span of the scenario used. Some benefit from better analysis of reservoir conditions and environmental hazard has been included in terms of the possibility of changed requirements for reinjection, but there are also other, frequently intangible, benefits from improved environmental protection that cannot be given a dollar value.

The time sequencing of the phases of development will have a significant impact on the priorities which may be given to specific logging problems. Exploration and assessment are the first steps in development and thus research to aid these steps has a greater urgency. On the other hand, much of the benefit from better assessment will not be realized until power comes on-line. Cost savings in the drilling program will be gained prior to this, which will enhance the present value of these benefits. This issue will be discussed further in terms of the quantitative benefit estimates.

2.3 IMPACTS OF IMPROVED LOG DATA

Improved data from well logging in geothermal areas can be valuable in virtually all aspects of geothermal field development. While logged data obviously is not available before drilling has occurred in an area, data from logs in previous wells can be valuable when exploratory drilling is undertaken for field expansion and the siting of new power plants. Logging in an exploratory well is also often undertaken in an attempt to determine if drilling should be continued and if a well has sufficient potential to warrant completion and testing. Reservoir assessment and modeling can be done with increased confidence if reliable information on formation characteristics can be obtained. The same data can aid in planning wells to reduce drilling costs. Environmental protection and the permit granting process can be affected regarding decisions about reinjection and protection against subsidence. The ability to monitor changes in the reservoir would be valuable in justifying the field operations plan. In the longer term, improved knowledge of the reservoir may be the key to reservoir management policies that could extend field life and conserve our scarce, high-quality hydrothermal resources. Another significant long-term benefit may come from the development of well stimulation programs. A detailed knowledge of downhole formation parameters will be needed for such a program. Table 2-1 lists a variety of uses of improved geothermal logging data. Those which can be most readily estimated quantitatively are shown first.

2.4 NEED FOR CALIBRATION

Apart from degradation of tool performance due to the temperatures involved, logging measurements with the same tools in geothermal and petroleum reservoirs can be performed with equal precision (repeatability), but with widely differing accuracy (calibration). The loss of accuracy arises from two sources:

Table 2-I. Impact of Improved Interpretation and Application of Logged Data

<u>IMPACT</u>	<u>ACTIVITY</u>	<u>REQUIREMENTS</u>
IMPROVED DRILLING SUCCESS RATE	EXPLORATION	BETTER INTERACTION WITH SURVEY DATA, NEW TECHNIQUES
	DEVELOPMENT PROGRAM	WELL SITING FROM RESERVOIR MODEL
REDUCED DRILLING COST	DEVELOPMENT PROGRAM RESERVOIR MODELING	PREPLANNING WELLS. IMPROVED OR MORE RAPID COMPLETION. BETTER SELECTION OF TOTAL DEPTH
REDUCED TESTING TIME	ASSESSMENT	REDUCED FLOW TESTING OF PRODUCTION WELLS BASED ON GREATER COMPARABILITY AND RELATION OF LOGGED PARAMETERS TO PRODUCTION CHARACTERISTICS
IMPROVED REINJECTION PROGRAM	ENVIRONMENTAL PROTECTION	JUSTIFICATION FOR LESS THAN 100% REINJECTION JUSTIFICATION FOR SHALLOW REINJECTION
	RESERVOIR MANAGEMENT	BETTER CONTROL OF REINJECTION WELL CLOGGING
IMPROVED WELL PUMP PLACEMENT	DEVELOPMENT PROGRAM	BETTER LOCATION OF FLASHING LEVEL AND SCALE CHARACTERISTICS
REDUCED PERMITTING	ENVIRONMENTAL PROTECTION	BETTER CONTROL OF SUBSIDENCE AND SEISMICITY; ABILITY TO MONITOR RESERVOIR

Table 2-1. Impact of Improved Interpretation and Application of Logged Data
(Continued)

REDUCED NUMBER OF EXPLORATORY WELLS	EXPLORATION	ACHIEVEMENT OF DEVELOPMENT AGREEMENTS BASED ON FEWER WELLS, REDUCED INVESTMENT "UP FRONT"
ACCELERATED DEVELOPMENT	RESERVOIR MODELLING	EARLIER UTILITY COMMITMENT
FACILITATION OF UNITIZATION AGREE- MENT OR OTHER REGULATIONS CON- TROLLING DEVELOPMENT	DEVELOPMENT PROGRAM	EARLIER AGREEMENT, MORE EQUITABLE ALLOTMENT OF REVENUES OR DRILLING RIGHTS
PLANT DESIGN	PLANT OPERATION	EASIER OR EARLIER DETERMINATION OF BRINE CHEMISTRY
IMPROVED WELL PERFORMANCE	RESERVOIR MANAGEMENT	DEVELOPMENT OF TECHNIQUES OF WELL STIMULATION
EXTENDED FIELD LIFE	RESERVOIR MANAGEMENT	RESERVOIR MONITORING, IMPROVED MODELLING, AND REINJECTION CONTROL
LOCATION OF NEW RESOURCES OR RESOURCES THAT WOULD OTHERWISE BE OVERLOOKED	EXPLORATION	NEW TECHNIQUES AND INTERACTION WITH SURFACE DATA. SPECIAL SIGNIFICANCE FOR DIRECT USE

- o Calibration test holes or pits have until very recently been unavailable for tools to be used in geothermal holes.
- o Incomplete logging suites caused by the unavailability of high-temperature rated sondes limit field calibration through cross plotting (redundancy), and when cross-plots can be made, the available petrophysical data from cores taken in geothermal formations is not sufficient to provide a good statistical basis for interpretation.

Moreover, there are new parameters of interest that do not appear in the oil and gas case, e.g., heat capacity, formation temperature, and formation thermal conductivity, as well as complications due to brine chemistry, unfamiliar metamorphosed lithologies, and possibly extensive fracture systems. As a consequence, the certainty of log interpreted parameters is lower for geothermal than for oil and gas field results.

Hovarth (1973) has made a study of the accuracy of petrophysical parameters derived from logging for oil and gas applications. Both systematic and unavoidable errors occur in log readings. The systematic errors arise from calibration failures and instrumental drift, both of which are more serious in geothermal applications than in oil and gas. The "unavoidable" errors refer to repeatability of the measurements and control the precision, rather than the absolute accuracy of the measurements; that is, they are statistical in nature and can be removed or reduced by averaging over several measurement points within a homogeneous interval, or by the all too expensive process of averaging results at the same point from repetitive logging runs.

Repeatability varies with the volume of investigation and is excellent for 16" normal, laterolog, SP, and acoustic logs, except at property boundaries, and is poorer for micro-resistivity tools. The emphasis of Hovarth's paper is on the less repeatable measurements from microlaterolog, and gamma and neutron tools. Several tools are sensitive to unknowns in the

tool travel path, and these are pronounced in geothermal wells with large bores and will influence small diameter hostile environment tools to a greater extent than tools of standard diameter. Finally, radioactivity logs are detecting statistically fluctuating phenomena, which again affects the recorded log values. The relative magnitudes of the unavoidable errors (in hydrocarbon logging) were found to range from less than 1% to a few percent with the exception of the microlaterolog for which errors as great as 10 percent occurred.

Uncertainties in calibration are systematic errors which are added to the errors of repeatability. It is standard practice to eliminate as many calibration constants from the interpretation process as the redundancy in data permits. For example, porosity from the density and neutron tools can be cross-plotted to determine the water line and shaliness independently of pre-run calibration of the tools. Hovarth shows that this procedure can cut calibration errors below 5%. Cross-plotting also contributes to the selection of appropriate empirical formulas for the log response as in the case of the resistivity-porosity cross plot. Without this control, errors of 10 to 20% can result (Lang, 1973).

Triporosity cross plots (Burke, et al., 1969), which involve porosity measurements from acoustic as well as density and neutron tools, remove another kind of absolute error from the interpretation process. The most sophisticated understanding of a reservoir requires a complete picture of the kinds of rock in the several formations through which a well has been drilled. Coring, a very expensive process, can give this information directly, and examination of drill cuttings can also be used but is often unsatisfactory. Much information about the lithology of different formations can be determined from a triporosity cross plot, which cross correlates porosity from different tools with the characteristics of the formation which influence these measurements. In oil and gas experience, a very large data base

of cores existed with which the reliability of the triporosity technique could be substantiated. The technique, in full development for the petroleum industry, cannot be applied yet for geothermal simply because it is not known where on the plots the unusual metamorphosed or intrusive lithologies would lie.

To realize the potential utility of this technique, and other logging applications (Duke, 1978), a considerable effort in core analysis will be needed to establish a geothermal data base, and some of the core measurements will have to be performed at temperatures and pressures which simulate the down-hole environment. Table 2-II shows a list of recommended properties to be evaluated for a broad range of geothermal cores. To prevent misinterpretation of these laboratory tests, a thorough chemical and petrographic analysis is recommended, which would include:

- o emission spectrography
- o neutron activation
- o x-ray spectroscopy
- o thin section petrography
- o x-ray diffraction
- o electron microscopy

TABLE 2-II. RECOMMENDED GEOTHERMAL CORE MEASUREMENTS*

Permeability (horizontal and vertical)

Porosity (total and effective)

Grain Density

Bulk Density (wet and dry)

Natural Gamma Ray Spectrum

*All except grain density and compressive strength should be performed at both standard and field conditions of temperature and pressure.

Gamma Backscatter Density
Compressive Strength
Acoustic Speed -- P Wave
Acoustic Speed -- S Wave
Electrical Resistivity (wet and dry)
Magnetic Susceptibility
Heat Capacity
Thermal Conductivity
Thermal Expansion
Thermal Diffusivity
Cation Exchange Capacity
Field Fluid Resistivity

If these measurements are extensively performed, then data will be available with which to facilitate the field recalibrations that are so important to producing valid log interpretations. They will enable the extension of the several empirical formulas, common in the log interpretation codes used by the major service companies, to the geothermal environment, and will further identify specific conditions under which naive use of those codes becomes invalid.

An example of the latter situation occurred in logging the Prudhoe Bay petroleum reservoir, where the presence of large amounts of pyrite required the service company to modify their standard interpretation techniques (Clavier, Hein, and Scola, 1976). For an oil and gas reservoir, this was an anomalous situation. For geothermal reservoirs, mineralization is expected to be much more common and to have significant influence on the response of electrical and nuclear logging tools. The recommended chemical petrographic studies will enable determination of the importance of lithologic characteristics to geothermal log interpretation.

Without appropriate calibration facilities and data redundancy to assist cross-plotting, calibration errors can exceed the unavoidable errors of repeatability by an order of magnitude. As a consequence, calibration errors of 10 to 20 percent propagate through the interpretation process and accumulate in the calculations used for the design of well tests and the computer simulation of long-range reservoir performance. Whereas the total error in calculations in favorable petroleum applications may amount to less than 10 percent; no firm upper bound can be placed on the total error in geothermal applications. Extensive comparisons must be made between as yet unavailable core data and logs for the many different types of geothermal reservoirs to predict the total log interpretation errors. Even then the situation will not compare favorably with the petroleum case until a sufficient variety of high-temperature sondes are available to provide good data redundancy, and until a good analytic foundation is laid for field recalibration in geothermal lithologies.

One way to view the situation is to assume that the calibration errors due to lithology are no larger than they are in petroleum fields before recalibrations (cross plots) are applied. That assumption places geothermal log interpretation at the same evolutionary stage in porosity determination that petroleum interpretation was in, perhaps fifteen years ago when the density-neutron cross plot was introduced, except that in geothermal the situation is worsened by logging in formations that differ notably from those in which the tools have been calibrated. With that assumption, however, the errors in porosity alone would be 10 to 20 percent. Sensitivity analysis on some of the basic formulas relating to reservoir quality have shown that errors of this magnitude may occur in several variables. Altogether, the error in first estimates of reservoir quality might be in the neighborhood of 40 to 80 percent, as opposed to 10 to 15 percent in favorable oil and gas fields.

The impact of such large uncertainties in geothermal reservoir quality has been clear historically. Only the most obvious geothermal resources have been commercially exploited, viz. the Geysers. Virtually the entire hydrothermal national resource remains unused and will until:

- o Either reservoir quality can be judged with an accuracy approaching petroleum state-of-the-art,
- o or the potential return on investment from geothermal is great enough to justify the increased risk of misjudgment.

3.0

ESTIMATION OF BENEFITS AND COSTS

As discussed above, two classes of benefits were estimated: savings related to field development, and economic benefits related to accelerated achievement of power-on-line. Information relevant to costs and savings as developed from SAI's analysis of geothermal development processes, from reviews of the record of drilling in geothermal areas, from an extensive review of relevant literature on logging and drilling costs, and from direct input and validation of assumptions obtained through contacts with representatives of the geothermal development industry (Appendix C contains a list of external contacts made in connection with the project). Sensitivity analysis of some existing reservoir modelling programs was undertaken to determine the dependence of reservoir assessment on various parameters. Accuracy of present log analysis and logging tools was examined with special attention to the impact of the lack of facilities for tool calibration under geothermal conditions. It was found that major improvements in resource assessment were possible with improved data on reservoir parameters. Nonetheless, a significant degree of judgment was necessarily involved in the estimates arrived at, so every effort was made to make conservative assessments of the possible benefits. An eight-year program was assumed. One million dollars a year was taken as a reference funding level, and the projected improvements were such as were felt to be reasonable in that context.

3.1

DEVELOPMENT SCENARIO

The degree to which geothermal development can be enhanced or costs lowered by well logging is obviously going to depend on the extent of postulated development. A scenario of development is required from which to project improvements. The geothermal development scenario developed by the MITRE Corporation was postulated for this study. The use of this scenario was appropriate since the scenario has also been the basis of other

cost/benefit studies of potential research efforts (MITRE, 1978), and it is obviously desirable that studies should be based on comparable assumptions.

The scenario estimates electrical development in the near-term at 30 potential geothermal resources. Direct applications of geothermal energy are not considered. Estimated resource depths and drilling costs are included. The calculations done in the present study are in 1979 constant dollars; since the cost estimates in the MITRE scenario are two years old, well costs were adjusted to 1979 dollars by assuming a 10 percent annual escalation in drilling costs. This is about the observed rate of increase of well costs for the last few years, and it provides cost estimates in the scenario that are in reasonable agreement with well cost estimates SAI has checked from other sources (Rigby, 1978 and Larson, 1978).

Table 3-I displays the resource areas considered. Well drilling is projected through 1990. The wells drilled for exploration, production, reinjection, and replacement of cooled production wells are included. Figure 3-I shows the total drilling scenario for all wells. Production and reinjection wells are assumed to be drilled two years before the first power-on-line. Exploration wells for power plant site selection are assumed to be drilled four years before power-on-line. Thus, the drilling scenario through 1990 includes all wells required for power plants through 1992. Power-on-line through 1992 is shown in Fig. 3-2. More detail on the scenario is contained in Appendix A.

The MITRE scenario can be criticized on several bases. Analyses of geothermal development done by SAI in other work suggest that the assumption that drilling must precede power-on-line by two to four years is excessive. Also, recent exploration has produced disappointing results at some of the resource areas

Table 3-I. Resource Areas and Assumed Mean Well Depths and Costs for the Development Scenario

(Temperature data is not available for the liquid-dominated (hydro) resource at the Geysers and the West Yellowstone area)

Site	Temperature (°C)	Depth (KM)	Well Prices (\$K)	
			Production	Reinjection
Geysers (Steam), CA	240	2.5	1214.	1214.
Salton Sea, CA	340	1.5	484.	484.
Valles Caldera, NM	240	1.5	1191.	1191.
Brady, NV	214	1.0	794.	794.
Brawley, CA	260	2.0	484.	484.
Roosevelt, UT	280	1.3	645.	645.
Beowawe, NV	240	1.5	1191.	1191.
Coso, CA	220	1.5	744.	744.
Mono-Long Valley, CA	220	1.5	744.	744.
Cove Fort/Sulfurdale, UT	200	2.0	1843.	1228.
Heber, CA	190	1.5	726.	484.
Geysers (Hydro), CA	--	2.5	1331.	1331.
East Mesa, CA	180	1.5	726.	484.
Steamboat, NV	210	0.8	397.	397.
Surprise Valley, CA	170	1.5	1117.	744.
Chandler, AZ	178	2.5	2070.	1379.
Leach, NV	170	2.5	2587.	1725.
Bruneau-Grandview, ID	200	2.5	2587.	1725.
Lassen, CA	240	1.5	744.	744.
Alvord, OR	200	2.0	2949.	1966.
Safford, AZ	200	2.5	2587.	1725.
Weiser/Crane Creek, ID	160	1.5	1117.	744.
Vale, OR	160	1.5	715.	477.
Thermo, UT	200	2.0	1475.	988.
Raft River, ID	140	2.0	1101.	734.
Glass Mountain, CA	210	2.5	1725.	1725.
Puna, HI	275	2.5	2760.	2760.
Mount Hood, OR	125	1.5	893.	595.
Baker Hot Springs, WA	165	2.5	2587.	1725.
W. Yellowstone, MT	--	2.5	1104.	1104.

Figure 3-1. Estimated Geothermal Drilling Through 1990

Figure 3-2. Projected Growth of Power On-Line

included. The entire pace of development has also been questioned as overly optimistic. However, it cannot be denied that the pace of geothermal development has shown a distinct acceleration in the past year. Further, present international developments certainly seem to suggest a gloomy prospect of further increases in the cost of energy. The discovery of new resources, such as Westmorland in the Imperial Valley, tends to offset disappointing results at other areas. And finally, the fact that the scenario is used only through 1992 (drilling to 1990) renders the benefit estimates very conservative since geothermal development will certainly continue and, indeed, expand. On balance, we believe that the MITRE scenario, while not ideal, supplies a good basis for the cost and benefit estimates.

3.2 BENEFIT CALCULATION

Benefits of five types were found to have a significant impact on development costs,

- o improved success rate
- o earlier identification (leading to less spending) of unsuccessful wells
- o less time required in flow testing wells
- o reduced well costs
- o reduced reinjection requirements.

The benefits can all be related to well drilling and well costs. Benefits were calculated in terms of the drilling scenario. The potential for reduced reservoir testing and earlier and more accurate assessment of the value and reliability of a resource can also lead to an acceleration of power-on-line, a benefit which can be estimated from the power-on-line scenario.

Estimating the extent of the improvements that might be achieved given an improvement in our abilities to interpret logged data from geothermal fields is not simple. The value of better information from the logs will vary from resource to resource and even from well to well. The scenario includes

resource areas with a variety of disparate characteristics. Differences among reservoirs and pure chance will ensure that development at some areas may be very greatly benefited while there may be other sites at which the logs will do nothing but confirm conclusions reached by other means. The cost of drilling a well can vary widely depending on the problems encountered, and obviously any cost savings that might be achieved will be at least as variable. Yet to calculate total benefits, it is necessary to project some sort of average. One of the most difficult problems is that we are dealing with incremental benefits. Log data will be used in addition to data obtained in other ways, such as flow testing and cuttings analysis. All together, it is very probable that the real benefits of improvements in the interpretation of geothermal well logs will take the form of minor improvements in the operations in many areas and a few major successes that might not have been achieved without the data drawn from the logs.

The improvement in logging geothermal wells was assumed to occur gradually over an eight-year period beginning in 1979 (thus no benefits were assumed for 1978, the first year of the GLIP). For each benefit area calculated, a maximum improvement (such as a 3 percent reduction in production well costs) was assumed to develop linearly from 1979 to 1986 and to remain constant thereafter. It is possible however that the benefits from the program could be enhanced by some different apportionment of funding or research effort. To investigate this the calculations were repeated based on achievement of the program in five years. This makes it possible to assess which benefits can be increased most by receiving extra emphasis. This will be discussed further in Section 3.4.

Appendix B gives more detail on calculation of benefits.

Drilling Success

Wells are sited largely on the basis of geological and geophysical survey data for an area and, for production wells, the reservoir model that is developed. Wells will be failures if they do not encounter formations of sufficient permeability or if they do not find high temperature fluids. Although the first well on a site obviously cannot benefit from log data, later drilling success can be enhanced, including both exploration for field expansion and production drilling.

One aspect of this can be simply a matter of locating the boundaries of the geothermal field. Wells drilled outside the limits of the hot or permeable zone will be failures. In some fields, especially those with intergranular porosity, the geothermal fluids may be fairly uniformly available within the reservoir limits, and the location of boundaries will be the main factor in drilling success. Many geothermal fields, however, have very complex geology and may be severely broken up by faults. Faults may be important either as aquacludes establishing limits of a field or as the dominant source of permeability. Locating highly permeable (generally fractured) zones is often the key to drilling success.

One type of data that may be of special relevance to well siting is inter-well correlation. This may help locate faults and also identify reservoir structures, which can aid modeling. Test wells are used to locate reservoir limits. In addition, lithologic information and knowledge of the dip angles of major faults can help ensure that a well will intersect a permeable zone.

Interpretation of surface geophysical surveys is basically an inversion problem, for which the solutions are generally non-unique. Combs (1978) emphasizes the value of geological and structural models plus a knowledge of the associated physical properties in urging extensive sample collection and laboratory testing. Logging can often provide the same data, in situ, at far less cost.

Logged data can also be used to assist interpretation of surface geological and geophysical data if the undisturbed formation properties can be inferred. The surface surveys most widely used in geothermal well siting seem to be heat flow (derived from thermal gradient and conductivity), gravity, and resistivity data. Airborne magnetic surveys are also often used because they are easily made. Differences of opinion exist on the value of seismic data, because of the difficulty of associating identifiable seismic signals with geothermal fluids. Telluric and magneto-telluric surveys may also find increasing application as familiarity with these techniques increases. Sharpening the modeling of geophysical anomalies associated with a field might help establish reservoir boundaries. True density data and formation thickness would aid gravity interpretation. For geothermal areas, because of the conductivity of the hot brine, electrical resistivity is a useful measurement. Interpretation of surface resistivity data is hampered, however, by the fact that both thickness and resistivity are unknown for the subsurface formations. Using log data in a geothermal field to establish resistivity values, thereby improving spatial resolution for surface resistivity studies, might be one example of a feasible synergism of surface and logged data. The value of seismic data might similarly be increased. Some work has been done in hydrocarbon exploration with interpreting high-density seismic data in terms of vertical interval velocity columns similar to sonic logs (Street, 1978). In conjunction with logs for successful wells in a geothermal field such an approach might enhance the value of seismic surveys.

Table 3-II shows the benefit projection from a few percent improvement in drilling success (Appendix B gives more detail).

Reduction of Expenditures on Unsuccessful Exploratory Wells

While some exploratory wells are either obviously successful or obviously unsuccessful, many are not so easily evaluated. The decisions to abandon drilling in a poor well or to perform cleanup, run a liner, and test a marginal well, are difficult and may determine a large fraction of the total cost of the well. The most crucial decision-making factor while drilling is the local formation temperature and thermal conductivity. Exploratory wells are usually sited in areas of high thermal gradient, and it is often necessary to decide if the heat source is a shallow, warm aquifer or a deeper, high-temperature source. Quick determination of true formation temperature away from the altered conditions near the borehole is important. Inference of formation thermal conductivity from logs could assist temperature equilibrium and heat flow calculations (Murphy and Lawton, 1977).

In deciding on clean up, completion, and testing, the estimation of whether there will be any permeability is also very important. Location and density of fracturing is often the crucial issue in this context. Table 3-III summarizes the estimate for this benefit. The benefit is calculated only for exploratory wells. Some benefit will undoubtedly also accrue for production wells, but since the formations will presumably then be better understood, it was assumed this would be a lesser effect.

Reduced Well Costs

Log data is used in the preparation of bit plans and other drilling plans for geothermal wells just as it is for other

Table 3-II. Benefit Due to Improved Drilling Success (10^6 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAM), CA	0.20	0.63	0.65	1.08	0.88	0.51	0.64	0.73	0.73	0.78	0.73	0.73
SALTON SEA, CA	0.00	0.00	0.04	0.02	0.11	0.11	0.13	0.19	0.20	0.21	0.22	0.23
VALLES CALDERA, NM	0.00	0.00	0.15	0.06	0.02	0.71	0.03	1.02	0.24	1.10	1.10	1.18
BRADY, NV	0.00	0.00	0.13	0.04	0.02	0.35	0.03	0.87	0.13	0.94	0.94	1.01
BRAWLEY, CA	0.00	0.00	0.05	0.00	0.09	0.04	0.21	0.24	0.26	0.27	0.29	0.31
ROOSEVELT, UT	0.00	0.00	0.05	0.03	0.01	0.16	0.01	0.23	0.09	0.38	0.38	0.40
BEOWAVE, NV	0.00	0.00	0.15	0.06	0.02	0.41	0.03	0.59	0.20	1.02	1.02	1.10
COSO, CA	0.00	0.04	0.00	0.04	0.24	0.29	0.37	1.07	1.03	1.12	0.28	0.37
MONO-LONG VALLEY, CA	0.00	0.04	0.00	0.00	0.24	0.00	0.57	0.11	0.09	0.72	0.09	0.16
COVE FORT/SULFURDALE, UT	0.00	0.09	0.00	0.00	0.56	0.00	0.85	0.26	1.03	1.05	1.84	1.91
HEBER, CA	0.00	0.00	0.00	0.00	0.26	0.00	0.40	0.11	0.84	0.84	0.91	0.98
GEYSERS (HYDRO), CA	0.00	0.03	0.00	0.07	0.86	1.04	1.32	1.63	1.75	1.88	2.00	2.13
EAST MESA, CA	0.00	0.00	0.00	0.00	0.26	0.05	0.04	0.46	0.04	0.08	0.08	0.08
STEAMBOAT, NV	0.00	0.02	0.00	0.00	0.12	0.03	0.02	0.25	0.02	0.42	0.04	0.08
SURPRISE VALLEY, CA	0.00	0.00	0.08	0.00	0.00	0.61	0.10	0.89	1.59	1.66	1.80	1.94
CHANDLER, AZ	0.00	0.00	0.16	0.00	0.00	0.93	0.00	0.33	0.33	2.61	1.37	0.37
LEACH, NV	0.00	0.00	0.00	0.26	0.00	0.00	1.63	0.26	0.44	2.31	4.17	4.36
BRUNEAD-CRANDVIEW, ID	0.00	0.00	0.00	0.26	0.00	0.00	0.88	0.26	0.36	2.38	2.38	2.58
LASSEN, CA	0.00	0.00	0.00	0.07	0.00	0.00	0.21	0.07	0.02	0.27	0.02	0.05
ALVORD, OR	0.00	0.00	0.00	0.29	0.00	0.00	1.01	0.29	0.41	1.56	1.56	1.68
SAFFORD, AZ	0.00	0.00	0.00	0.26	0.00	0.00	0.88	0.00	0.10	0.10	0.10	0.10
WEISER/CRAVE CREEK, ID	0.00	0.00	0.00	0.00	0.14	0.00	0.00	1.12	0.11	2.22	2.22	2.42
VALE, OR	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.72	0.07	0.78	0.78	0.84
THERMO, UT	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.58	0.00	0.21	0.21	1.36
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.07	0.00	0.00	1.93	0.00	2.00	0.18	0.36
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.88	0.00	0.09
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.28	1.60	2.93	3.06
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	1.34	0.00	0.13
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	2.10	0.00	0.21
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	1.64	0.00	0.17
TOTALS	0.20	0.85	1.46	2.54	4.19	8.25	10.96	14.18	10.41	34.42	27.64	30.39

Table 3-III. Reduced Expenditures on Unsuccessful Wells (10^6 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYERS (STEAM), CA	0.03	0.07	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
RAILTON SEA, CA	0.00	0.00	0.04	0.03	0.07	0.08	0.09	0.11	0.11	0.11	0.11	0.11
VALLES CALDERA, NM	0.00	0.00	0.00	0.13	0.00	0.20	0.00	0.26	0.26	0.26	0.26	0.26
BRADY, NV	0.00	0.00	0.00	0.09	0.00	0.13	0.00	0.18	0.18	0.18	0.18	0.18
BRADLEY, CA	0.00	0.00	0.04	0.00	0.07	0.08	0.09	0.11	0.11	0.11	0.11	0.11
ROOSEVELT, UT	0.00	0.00	0.00	0.07	0.00	0.11	0.00	0.14	0.14	0.14	0.14	0.14
BEOWAVE, NV	0.00	0.00	0.00	0.13	0.00	0.20	0.00	0.26	0.26	0.26	0.26	0.26
COSO, CA	0.00	0.08	0.00	0.00	0.10	0.12	0.14	0.17	0.00	0.00	0.00	0.00
MORO-LONG VALLEY, CA	0.00	0.08	0.00	0.00	0.10	0.00	0.00	0.17	0.00	0.00	0.00	0.00
COVE FORT/SULFURDALE, UT	0.00	0.21	0.00	0.00	0.26	0.00	0.36	0.41	0.41	0.41	0.41	0.41
HEBER, CA	0.00	0.00	0.00	0.00	0.10	0.00	0.14	0.16	0.16	0.16	0.16	0.16
GEYSERS (HYDRO), CA	0.00	0.08	0.00	0.15	0.19	0.23	0.27	0.31	0.31	0.31	0.31	0.31
EAST MESA, CA	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
STEAMBOAT, NV	0.00	0.04	0.00	0.00	0.00	0.07	0.00	0.09	0.00	0.00	0.00	0.00
SURPRISE VALLEY, CA	0.00	0.00	0.19	0.00	0.00	0.19	0.22	0.25	0.25	0.25	0.25	0.25
CHANDLER, AZ	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.46	0.46	0.00	0.00	0.00
LEACH, NV	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.58	0.58	0.58	0.58	0.58
BRUNEAU-GRANDVIEW, ID	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.58	0.58	0.58	0.58	0.58
LASSER, CA	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00
ALVORD, OR	0.00	0.00	0.00	0.66	0.00	0.00	0.00	0.66	0.66	0.66	0.66	0.66
RAFFORD, AZ	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WEISER/CRAKE CREEK, ID	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.25	0.25	0.25	0.25	0.25
VALE, OR	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.16	0.16	0.16	0.16	0.16
THERMO, UT	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.33	0.33	0.33
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.24	0.00	0.00	0.00	0.00
CLARK MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	1.07	0.00	0.61	0.61	0.61	0.61
MOUNT BOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00
BAKER BOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.00	0.00	0.00	0.00	0.00
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00	0.00	0.00
TOTALS	0.03	0.56	0.71	3.26	1.96	1.53	4.86	5.70	5.48	5.35	5.35	5.35

drilling. Geothermal formations frequently involve igneous and metamorphic rock types not commonly encountered in petroleum drilling; so experience in lithologic identification and its relationship to drillability will be important for developing geothermal formations. Determination of the dominant fracture orientation can also play a very valuable part in cutting drilling costs if the wells can be controlled to help assure the intersection of a maximum number of fractures. If a well departs from vertical at an angle paralleling the dominant fracturing, it may not achieve good permeability despite good siting. Inter-well correlation can reveal dip angles, but techniques for inferring fracture orientation from a single well would certainly be desirable. Surface geophysical data can also be used in planning drilling (Dummont and Purdy, 1976) and the application of log data to improve the inversion of the surface data could again be valuable. Formation properties also affect well completion practices (Aguilera and van Poolen, 1979a and Shell and Tragesser, 1972).

Selection of total drilling depth is another problem. In many geothermal reservoirs, decisions based on target depths or geologic goals may not be satisfactory especially if the target is not a stratified formation but rather the location of high temperature, fractured zones. Since temperature around the wellbore is distorted by the drilling process and total permeability is hard to judge, there is a tendency to drill to extra depth, as much as 500 to 600 feet (150 to 200 meters) (Zebal, 1979). Since per foot cost of drilling in geothermal formations is often two or three times greater than for petroleum wells, logging a well prior to the decision to terminate drilling could be economically reasonable if temperature and, more importantly, permeability could be reliably established.

There was general agreement among those individuals contacted involved in development that better log data might cut drilling cost at least a few percent. Table 3-IV shows the benefit estimate.

Table 3-IV. Well Cost Savings (10^6 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAD), CA	0.20	0.43	0.65	1.08	0.88	0.51	0.44	0.73	0.73	0.73	0.73	0.73
SALTON SEA, CA	0.00	0.00	0.04	0.02	0.11	0.11	0.13	0.19	0.20	0.21	0.22	0.23
VALLES CALDERA, NM	0.00	0.00	0.18	0.06	0.02	0.71	0.03	1.02	0.24	1.10	1.10	1.18
BRADY, NV	0.00	0.00	0.13	0.04	0.02	0.35	0.03	0.87	0.13	0.94	0.94	1.01
BRADLEY, CA	0.00	0.00	0.03	0.00	0.09	0.04	0.21	0.24	0.26	0.27	0.29	0.31
ROOSEVELT, UT	0.00	0.00	0.03	0.03	0.01	0.16	0.01	0.23	0.09	0.38	0.38	0.40
DEQVAVE, NV	0.00	0.00	0.13	0.06	0.02	0.41	0.03	0.59	0.20	1.02	1.02	1.10
COSO, CA	0.00	0.04	0.00	0.04	0.24	0.29	0.37	1.07	1.03	1.12	0.28	0.37
MONO-LONG VALLEY, CA	0.00	0.04	0.00	0.00	0.24	0.00	0.57	0.11	0.09	0.72	0.09	0.16
COVE FORT/SULFURDALE, UT	0.00	0.09	0.00	0.00	0.56	0.00	0.85	0.26	1.03	1.03	1.04	1.91
HEBER, CA	0.00	0.00	0.00	0.00	0.26	0.00	0.40	0.11	0.84	0.84	0.91	0.98
GEYSERS (HYDRO), CA	0.00	0.03	0.00	0.07	0.86	1.04	1.32	1.63	1.73	1.88	2.00	2.13
EAST MESA, CA	0.00	0.00	0.00	0.00	0.26	0.03	0.04	0.46	0.04	0.08	0.08	0.08
STEAMBOAT, NV	0.00	0.02	0.00	0.00	0.12	0.03	0.02	0.23	0.02	0.42	0.04	0.08
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.61	0.10	0.89	1.59	1.66	1.80	1.94
CHANDLER, AZ	0.00	0.00	0.16	0.00	0.00	0.93	0.00	0.33	0.33	2.61	1.37	0.37
LEACH, NV	0.00	0.00	0.00	0.26	0.00	0.00	1.63	0.26	0.44	2.31	4.17	4.36
BRUNEAU-CRANVIEW, ID	0.00	0.00	0.00	0.26	0.00	0.00	0.88	0.26	0.36	2.38	2.38	2.58
LASSER, CA	0.00	0.00	0.00	0.07	0.00	0.00	0.21	0.07	0.02	0.27	0.02	0.03
ALYDOR, OR	0.00	0.00	0.00	0.29	0.00	0.00	1.01	0.29	0.41	1.56	1.56	1.68
SAFFORD, AZ	0.00	0.00	0.00	0.26	0.00	0.00	0.88	0.00	0.10	0.10	0.10	0.10
WEISER-CRANE CREEK, ID	0.00	0.00	0.00	0.00	0.14	0.00	0.00	1.12	0.11	2.22	2.22	2.42
VALE, OR	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.72	0.07	0.78	0.78	0.84
THERMO, UT	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.58	0.00	0.21	0.21	1.36
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.07	0.00	0.00	1.93	0.00	2.00	0.18	0.36
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.88	0.00	0.09
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.28	1.60	2.93	3.06
MOUNT BOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	1.34	0.00	0.13
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	2.10	0.00	0.21
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	1.66	0.00	0.17
TOTALS	0.20	0.83	1.46	2.84	4.19	5.23	10.96	14.18	10.41	34.43	27.64	80.99

Reduced Flow Testing

Because flow testing is linked to the high capital investment involved in constructing the power plant, it plays a major role in development. Testing of the initial exploratory wells may be controlled by the lack of a reinjection well, superceding any other consideration. But later wells will be flowed for weeks or months before a decision is even made to commit to building a power plant. Even after a plant is built, new wells will be tested extensively to determine performance characteristics before hooking them up. Flow testing can involve weeks or months at costs of tens of thousands of dollars per well. If logs can contribute data such as porosity and interval thickness (or especially permeability), the interpretation of test data can be simplified (Aguilera and Van Poolen, 1979b).

If experience on a resource made it possible to relate production characteristics to well log characteristics, the need for testing later production wells to predict their behavior might be reduced. The role of the GLIP in compiling logging records on a variety of wells will make a valuable contribution to this as will the support of new research. Table 3-V gives the benefit estimate.

Reduced Reinjection Requirements

Produced brine is reinjected into the reservoir for the purpose of brine disposal, protection against subsidence, and protection against loss of pressure or permeability. Often, natural recharge will be sufficient to allow less than 100 percent reinjection, but without good evidence of this, 100 percent reinjection may be required to ensure protection of the environment. Establishing that fluids can be reinjected in lesser quantities or at shallower levels than they are produced can provide a major cost saving, especially for flashed steam plants (in flashed steam plants a portion of the produced brine

Table 3-V. Reduced Flow Testing (10^6 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAM), CA	0.10	0.32	0.31	0.55	0.41	0.17	0.21	0.24	0.24	0.24	0.24	0.24
SALTON SEA, CA	0.00	0.00	0.03	0.00	0.11	0.10	0.12	0.19	0.29	0.21	0.22	0.23
VALLES CALDERA, NH	0.00	0.00	0.09	0.00	0.01	0.36	0.01	0.50	0.04	0.53	0.53	0.53
BRADY, NV	0.00	0.00	0.12	0.00	0.01	0.23	0.02	0.67	0.04	0.70	0.70	0.74
BRADLEY, CA	0.00	0.00	0.03	0.00	0.08	0.01	0.23	0.27	0.28	0.30	0.31	0.32
ROOSEVELT, UT	0.00	0.00	0.06	0.00	0.01	0.12	0.01	0.16	0.02	0.32	0.32	0.34
BEOWAVE, NV	0.00	0.00	0.09	0.00	0.01	0.18	0.01	0.26	0.03	0.50	0.50	0.53
COSO, CA	0.00	0.00	0.00	0.00	0.18	0.22	0.27	0.92	0.93	0.98	0.15	0.20
MONO-LONG VALLEY, CA	0.00	0.00	0.00	0.00	0.18	0.00	0.53	0.02	0.43	0.64	0.03	0.08
COVE FORT/SULFURDALE, UT	0.00	0.00	0.00	0.00	0.17	0.00	0.25	0.02	0.30	0.30	0.59	0.61
HEBER, CA	0.00	0.00	0.00	0.00	0.21	0.00	0.31	0.02	0.71	0.71	0.73	0.79
GEYSERS (HYDRO), CA	0.00	0.00	0.00	0.00	0.39	0.47	0.58	0.70	0.74	0.77	0.81	0.85
EAST MESA, CA	0.00	0.00	0.00	0.00	0.23	0.00	0.02	0.42	0.02	0.03	0.03	0.03
STEAMBOAT, NV	0.00	0.00	0.00	0.00	0.21	0.00	0.02	0.36	0.02	0.71	0.04	0.08
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.47	0.91	0.93	0.98	1.03
CHANDLER, AZ	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.02	0.02	0.06	0.44	0.07
LEACH, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.03	0.53	1.04	1.07
BRUNEAU-GRANDVIEW, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.02	0.56	0.56	0.59
LASSER, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.01	0.24	0.01	0.03
ALVORD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.02	0.29	0.29	0.30
SAFFORD, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.02	0.02	0.02	0.02
WEISER/CRAZE CREEK, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	1.30	1.30	1.37
VALE, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.67	0.67	0.70
THERMO, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.02	0.02	0.56
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	1.22	0.07	0.13
CLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.02
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.67	0.69
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	0.06
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.00	0.03
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	0.00	0.06
TOTALS	0.10	0.32	0.73	0.55	2.24	2.52	3.96	7.91	4.63	16.96	11.81	12.33

is converted into steam and becomes part of the cooling tower water upon condensation, thereby reducing the plant's water requirement if extra reinjection water is not required). Interaction with regulatory bodies, especially concerning subsidence, seems likely to be of considerable importance in many areas. The ability to establish either favorable recharge conditions or communication between a proposed reinjection zone and the production zone could be very valuable. Knowledge of the reservoir structure and the bulk mechanical properties of the rock, obtained from acoustic logs, could assist prediction of the degree of subsidence hazard. In addition, the ability to monitor the reservoir for compaction could be a major contribution, since it would then be possible to detect a problem before the effect was manifested at the surface, allowing time to change reinjection strategy to correct the problem. Compaction or densification due to deposition could also be a warning of permeability impairment. Table 3-VI shows this benefit.

Accelerated Power-On-Line

Benefits were also estimated based on the earlier achievement of power-on-line. A number of factors could impact the rate of development. Improved drilling success and reduced well testing time will accelerate field development. Reduced risks and costs could encourage investment. However, for the most part, development is not paced by the drilling activity. External factors such as cost of competing power sources will significantly affect the rate of investment. Once development begins, regulatory processes and surface construction appear to be rate controlling. Figure 3-3 reproduces part of a projection of development potential at Puna, Hawaii prepared by SAI. It can be observed that drilling activities are not rate controlling except at one point -- the exploratory drilling and testing prior to the commitment to power plant construction at the site. Analysis of the potential improvement in the accuracy of reservoir assessment and discussions with developers have led to the

Table 3-VI. Reduced Reinjection (10^6 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAM), CA	0.03	0.08	0.07	0.13	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SALTON SEA, CA	0.00	0.00	0.03	0.00	0.14	0.00	0.10	0.15	0.13	0.15	0.15	0.15
VALLES CALDERA, NM	0.00	0.00	0.22	0.00	0.00	0.67	0.00	0.60	0.00	0.60	0.60	0.60
BRADY, NV	0.00	0.00	0.21	0.00	0.00	0.42	0.00	0.56	0.00	0.56	0.56	0.56
BRADLEY, CA	0.00	0.00	0.07	0.00	0.12	0.00	0.17	0.19	0.19	0.19	0.19	0.19
ROOSEVELT, UT	0.00	0.00	0.15	0.00	0.00	0.29	0.00	0.19	0.00	0.39	0.39	0.39
BEOWAVE, NV	0.00	0.00	0.22	0.00	0.00	0.45	0.00	0.30	0.00	0.60	0.60	0.60
COSO, CA	0.00	0.00	0.00	0.00	0.28	0.33	0.20	0.67	0.67	0.67	0.00	0.00
HONO-LONG VALLEY, CA	0.00	0.00	0.00	0.00	0.28	0.00	0.59	0.00	0.00	0.45	0.00	0.00
COVE FORT/SULFURDALE, UT	0.00	0.00	0.00	0.00	0.23	0.00	0.32	0.00	0.37	0.37	0.74	0.74
WEBER, CA	0.00	0.00	0.00	0.00	0.11	0.00	0.15	0.00	0.34	0.34	0.34	0.34
GEYSERS (HYDRO), CA	0.00	0.00	0.00	0.00	0.86	0.52	0.60	0.69	0.69	0.69	0.69	0.69
EAST MESA, CA	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.19	0.00	0.00	0.00	0.00
STEAMBOAT, NV	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.28	0.00	0.28	0.00	0.00
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.33	0.67	0.67	0.67	0.67
CHANDLER, AZ	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	1.10	0.55	0.00
LEACH, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.86	1.72	1.72
BRUNEAU-CRANDVIEW, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	1.03	1.03	1.03
LASSEN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.37	0.00	0.00
ALVORD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.59	0.59	0.59
SAFFORD, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00
WEISER-CRANE CREEK, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.89	0.89	0.89
VALE, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.29	0.29	0.29
THELWYD, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.59
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.00	0.77	0.00	0.00
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.21	0.00	0.00
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.21	2.21	2.21
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	0.00	0.00
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95	0.00	0.00
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.43	0.00	0.00
TOTALS	0.03	0.08	1.00	0.13	2.39	3.42	4.62	5.98	3.08	19.95	12.20	12.23

Figure 3-3. Puna Power Plant Scenario (20 MW).

conclusion that the number of wells needed prior to utility commitment might be reduced. In addition, if log data facilitated the reconciliation of geophysical and geological data with the reservoir model, some analysis time might be saved by the field developer. Also, at some fields, following utility commitment, additional time may be saved if better reservoir data can reduce regulatory permitting problems. An acceleration varying from zero to three months (depending on the assumed linear achievement of logging improvements) was postulated. It was assumed that this would not be cumulative for each plant at a site, but rather that the first plant at a site could be accelerated (the time savings was assumed to occur three years prior to the on-line date) and that subsequent plants would follow the first plant without any additional contraction in the time line.

The value of the additional power that could be produced was not calculated as the benefit resulting, since this power will simply displace power from other sources. Instead, an equivalent number of barrels of oil was estimated based on an 80 percent load factor for the geothermal plants and a 40 percent conversion efficiency for the oil. In order to discount this savings for present value, a dollar savings was computed at a rate of \$16 per barrel. Total undiscounted benefit was 117 million dollars; however certain additional calculations were made as explained in the next section.

3.4 TIME PHASING

We must also consider the possibility that the total benefits of the program can be increased by placing emphasis on some research efforts early in the program. To investigate this possibility, the benefit computation was repeated assuming that the improvements in log interpretation were achieved in five years instead of eight. Table 3-VII summarizes our findings.

Table 3-VII. Time Phasing Summary

(Millions of 1979 dollars)

<u>Benefit Type</u>	<u>8-year undisc</u>	<u>5-year undisc</u>	<u>8-year 10%dis</u>	<u>5-year 10%dis</u>
Success Rate	142.5	151.3	64.4	70.6
Unsuccessful Exploratory Wells	40.1	45.3	20.3	24.0
Flow Tests	63.6	67.3	28.8	31.4
Well Costs	142.5	151.3	64.4	70.6
Reduced Reinjection	65.1	69.1	29.3	32.0
Scenario Acceleration	117.0	164.6	43.8	62.5

Clearly, a significant gain, close to 50%, is possible in the benefits from accelerating power-on-line. The reason for this substantial increase is that, while the actual benefit is not realized until the power plant begins operation, the decisions regarding utility commitment and permitting required to initiate development on a resource area must be made two or three years before the first plant comes on-line. These decisions, therefore, come very early in the development of a resource while the benefits relating to cost reductions are spread out over the whole period of development in a resource area.

Based on this finding, it would seem reasonable to recommend that in the primary (but certainly not exclusive) emphasis in the first few years of the GLIP should be on those log interpretation problems the solution of which will contribute to scenario acceleration, which will mainly result from improved assessment of resource reliability and size. Since the data needed for resource assessment also contributes to the other benefits, it should be possible to achieve the increase in benefits for scenario acceleration without retarding the achievement of other benefits. Therefore our total benefit estimate

will be based on the eight-year development of the benefits related to field development costs and the five-year development of the benefits from scenario acceleration. Tables 3-VIII and 3-IX show oil displaced and the dollar equivalent for power-on-line acceleration with the five year assumption.

Several other points should also be noted. The second greatest percentage increase (about 20% of the discounted benefit) was for the benefits related to identifying the potential of exploratory wells. The most significant factor here is the determination of the temperature/thermal conductivity of the formation rock. Benefits accruing in the exploration process may also produce secondary indirect benefits which have not been included in the benefit estimate. These are the possibility that better success and lower risk in exploration may induce increased investment in exploration, and the possibility of discovering a resource that would otherwise be neglected.

Another point is that the increase in total benefits in going from the eight-year to the five-year assumption is not large. It would therefore appear that the total benefit of going to a shorter program at a higher annual funding is limited. Finally, the lowest benefit increases from the five-year assumption are for reduced flow testing of production wells and reduced reinjection requirements. Flow testing is closely linked to reservoir assessment. However, the result for reinjection suggests that work on measurements to determine the bulk mechanical properties of reservoir rock or work on monitoring compaction could be left for later in the program.

3.5 LOGGING COSTS

The costs of logging the wells must be estimated and subtracted from the gross benefits in order to obtain the net expected benefit from the improved logging. All exploration, production, and replacement wells were assumed to be logged at an

Table 3-VIII. Equivalent Barrels of Oil Displaced by Accelerating Power-On-Line (Thousands of Barrels)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	TOTAL
GEYSERS (STEAM), CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SALTON SEA, CA	0.0	0.0	0.0	0.0	18.8	0.0	37.5	28.1	28.1	37.5	37.5	37.5	37.5	37.5	300.0
VALLES CALDERA, NM	0.0	0.0	0.0	0.0	18.8	0.0	0.0	37.5	0.0	37.5	0.0	37.5	37.5	37.5	206.3
BRADY, NV	0.0	0.0	0.0	0.0	18.8	0.0	0.0	18.8	0.0	37.5	0.0	37.5	37.5	37.5	187.5
BRAWLEY, CA	0.0	0.0	0.0	0.0	18.8	0.0	18.8	0.0	37.5	37.5	37.5	37.5	37.5	37.5	262.5
ROOSEVELT, UT	0.0	0.0	0.0	0.0	18.8	0.0	0.0	18.8	0.0	18.8	0.0	37.5	37.5	37.5	168.8
BEOWAVE, NV	0.0	0.0	0.0	0.0	18.8	0.0	0.0	18.8	0.0	18.8	0.0	37.5	37.5	37.5	168.8
COSO, CA	0.0	0.0	0.0	0.0	0.0	0.0	37.5	37.5	37.5	112.5	112.5	112.5	0.0	0.0	430.0
MONO-LONG VALLEY, CA	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	75.0	0.0	0.0	75.0	0.0	0.0	187.5
COVE FORT/SULFURDALE, UT	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	37.5	0.0	37.5	37.5	75.0	75.0	300.0
HEBER, CA	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	37.5	0.0	75.0	75.0	75.0	75.0	375.0
GEYSERS (HYDRO), CA	0.0	0.0	0.0	0.0	0.0	0.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0	600.0
EAST MESA, CA	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	0.0	37.5	0.0	0.0	0.0	0.0	75.0
STEAMBOAT, NV	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	0.0	37.5	0.0	75.0	0.0	0.0	150.0
SURPRISE VALLEY, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.9	0.0	46.9	93.8	93.8	93.8	93.8	468.8
CHANDLER, AZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	46.9	0.0	0.0	0.0	93.8	46.9	0.0	187.5
LEACH, NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	0.0	56.3	112.5	112.5	337.5
BRUNEAU-GRANDVIEW, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	0.0	112.5	112.5	112.5	393.8
LASSEN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	0.0	56.3	0.0	0.0	112.5
ALVORD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	0.0	56.3	56.3	56.3	225.0
SAFFORD, AZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	56.3	0.0	0.0	0.0	0.0	0.0	56.3
WEISER/CRAVE CREEK, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.6	0.0	131.3	131.3	131.3	459.4
VALE, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.6	0.0	65.6	65.6	65.6	262.5
THERMO, UT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.6	0.0	0.0	0.0	131.3	196.9
RAFT RIVER, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.6	0.0	65.6	0.0	0.0	131.3
CLASS MOUNTAIN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	75.0
PUNA, HI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	150.0	300.0	300.0	750.0
MOUNT HOOD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	75.0
BAKER HOT SPRINGS, WA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	75.0
W. YELLOWSTONE, MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	75.0
TOTALS	0.0	0.0	0.0	0.0	112.5	0.0	256.3	328.1	609.4	789.4	468.8	1856.3	3104.8	2148.3	17912.5

Table 3-IX. Benefits Due to Acceleration of Power-On-Line Calculated From Table 3-VIII at \$16 Per Barrel of Oil Equivalent (10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
GEYSERS (STEAD), CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SALTON SEA, CA	0.00	0.00	0.00	0.00	0.48	0.00	0.96	0.72	0.72	0.96	0.96	0.96	0.96	0.96
VALLES CALDERA, NM	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.96	0.00	0.96	0.00	0.96	0.96	0.96
BRADY, NV	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.48	0.00	0.96	0.00	0.96	0.96	0.96
BRADLEY, CA	0.00	0.00	0.00	0.00	0.48	0.00	0.48	0.00	0.96	0.96	0.96	0.96	0.96	0.96
ROOSEVELT, UT	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.48	0.00	0.48	0.00	0.96	0.96	0.96
BEOWAVE, NV	0.00	0.00	0.00	0.00	0.48	0.00	0.00	0.48	0.00	0.48	0.00	0.96	0.96	0.96
COSO, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.96	0.96	2.88	2.88	2.88	0.00	0.00
HONO-LONG VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.00	1.92	0.00	0.00	1.92	0.00	0.00
COVE FORT/SULFURDALE, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.96	0.00	0.96	0.96	1.92	1.92
HEBER, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.96	0.00	1.92	1.92	1.92	1.92
GEYSERS (HYDRO), CA	0.00	0.00	0.00	0.00	0.00	0.00	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92
EAST MESA, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.00	0.96	0.00	0.00	0.00	0.00
STEAMBOAT, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.96	0.00	0.00	0.96	0.00	1.92	0.00	0.00
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	1.20	2.40	2.40	2.40	2.40
CHANDLER, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.00	2.40	1.20	0.00
LEACH, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	1.20	2.40	2.40
BRUNEAU-CRANVIEW, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	2.40	2.40	2.40
LASSEN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	1.20	0.00	0.00
ALVORD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	1.20	1.20	1.20
SAFFORD, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.00
WEISER/CRAVE CREEK, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	2.40	2.40	2.40
VALE, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	1.20	1.20	1.20
THERMO, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00	0.00	2.40
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	1.20	0.00	0.00
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.40	4.80	4.80
MOUNT BOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	0.00
TOTALS	0.00	0.00	0.00	0.00	2.88	0.00	9.12	8.40	14.40	17.52	12.00	40.08	29.82	30.72

average cost of \$25 000 each, and 5% of active production wells were assumed to be re-logged annually at a rate of \$15 000 each. Table 3-X shows the estimated costs. It will be observed that in 1979 and 1980 costs exceed benefits. This is reasonable since some benefits will not be realized until some years after the data are taken.

3.6 APPORTIONMENT OF BENEFITS BETWEEN TOOL DEVELOPMENT AND LOG INTERPRETATION

The benefit estimates thus far obtained represent estimates of the benefit of improved well logging data in geothermal reservoirs. These benefits will depend on both obtaining and interpreting the data. Many hydrothermal reservoirs are too hot to be logged with currently available tools. A number of logging tools are advertised to withstand temperatures of 200 or 210°C; most will bear improvement. Federally funded research is also actively addressing tool development (Lamers, 1978). Seven of the resource areas in the scenario are assumed to have temperatures below 175°C. These areas contribute about 25 percent of the estimated benefits. In order to apportion benefits between tool development and log interpretation, it was assumed that 100 percent of the benefits for areas with temperatures less than 175°C could be attributed to log interpretation. For other areas, the benefits were assumed to be split evenly. Table 3-XI and Figure 3-4 summarize the findings.

3.7 OTHER BENEFITS

The quantitative benefit estimates in Table 3-XI reflect only near-term, hydrothermal electric development. A variety of other benefits that are less readily quantified will also accrue, and the fact that they are more difficult to estimate should not lead to their being ignored. The most obvious of these is the fact that benefits will continue to be realized after 1992. Indeed, since geothermal development can be expected to continue

Table 3-X. Estimates of Logging Costs (10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAM), CA	1.21	1.85	1.32	1.89	1.09	0.61	0.68	0.68	0.68	0.68	0.68	0.68
SALTON SEA, CA	0.00	0.00	0.22	0.13	0.34	0.29	0.31	0.38	0.40	0.43	0.46	0.48
VALLES CALDERA, NH	0.00	0.00	0.27	0.13	0.04	0.71	0.04	0.78	0.23	0.85	0.85	0.93
BRADY, NV	0.00	0.00	0.38	0.13	0.05	0.55	0.05	0.97	0.23	1.07	1.07	1.17
BRADLEY, CA	0.00	0.00	0.28	0.00	0.29	0.14	0.46	0.46	0.50	0.84	0.88	0.62
ROOSEVELT, UT	0.00	0.00	0.17	0.13	0.02	0.32	0.02	0.35	0.17	0.84	0.84	0.59
BEOWAVE, NV	0.00	0.00	0.27	0.13	0.04	0.44	0.04	0.47	0.20	0.78	0.78	0.85
COSO, CA	0.00	0.25	0.00	0.13	0.47	0.47	0.52	1.27	1.19	1.32	0.41	0.55
MORO-LONG VALLEY, CA	0.00	0.25	0.00	0.00	0.47	0.00	0.75	0.17	0.14	0.84	0.14	0.23
COVE FORT/SULFURDALE, UT	0.00	0.25	0.00	0.00	0.45	0.00	0.49	0.17	0.53	0.83	0.90	0.94
NEBER, CA	0.00	0.00	0.00	0.00	0.52	0.00	0.58	0.18	1.03	1.03	1.13	1.24
GEYSERS (HYDRO), CA	0.00	0.13	0.00	0.13	0.88	0.88	0.97	1.07	1.17	1.27	1.36	1.46
EAST MESA, CA	0.00	0.00	0.00	0.00	0.47	0.13	0.06	0.54	0.06	0.12	0.12	0.12
STEAMBOAT, NV	0.00	0.25	0.00	0.00	0.40	0.13	0.05	0.58	0.05	0.90	0.10	0.21
SURPRISE VALLEY, CA	0.00	0.00	0.25	0.00	0.00	0.65	0.13	0.72	1.24	1.31	1.45	1.58
CHANDLER, AZ	0.00	0.00	0.25	0.00	0.00	0.50	0.00	0.19	0.19	1.06	0.56	0.20
LEACH, NV	0.00	0.00	0.00	0.25	0.00	0.00	0.60	0.13	0.20	0.80	1.40	1.48
BRUNZAU-CRANVIEW, ID	0.00	0.00	0.00	0.25	0.00	0.00	0.32	0.13	0.17	0.82	0.82	0.90
LASSEN, CA	0.00	0.00	0.00	0.25	0.00	0.00	0.27	0.13	0.04	0.31	0.04	0.07
ALVORD, OR	0.00	0.00	0.00	0.25	0.00	0.00	0.32	0.13	0.17	0.49	0.49	0.53
SAPFORD, AZ	0.00	0.00	0.00	0.25	0.00	0.00	0.32	0.00	0.04	0.04	0.04	0.04
WEISER/CRAKE CREEK, ID	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.88	0.13	1.72	1.72	1.92
VALE, OR	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.88	0.13	0.97	0.97	1.07
THERMO, UT	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.32	0.00	0.17	0.17	0.82
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.13	0.00	0.00	1.50	0.00	1.55	0.18	0.36
CLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.42	0.00	0.04
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.13	0.52	0.92	0.98
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	1.25	0.00	0.16
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.67	0.00	0.00
V. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	1.25	0.00	0.16
TOTALS	1.21	2.97	3.42	3.71	6.42	5.81	8.22	13.02	8.97	24.27	17.87	20.48

Table 3-XI. Benefits (10^6 1979 Dollars)

Year	Field	Power	Costs	Total	5% Discount Rate	10% Discount Rate
1979	0.5	0	1.2	-0.7	-0.7	-0.7
1980	2.6	0	3.0	-0.4	-0.4	-0.3
1981	5.4	0	3.4	2.0	1.8	1.6
1982	9.0	0	3.7	5.3	4.6	4.0
1983	15.0	2.8	6.4	11.4	9.4	7.8
1984	18.0	0	5.8	12.2	9.6	7.6
1985	35.5	9.1	8.2	36.4	27.2	20.5
1986	47.9	8.3	13.0	43.2	30.7	22.2
1987	34.0	14.4	9.0	39.4	26.7	18.4
1988	111.1	17.5	24.3	104.3	67.2	44.2
1989	84.1	12.1	17.9	78.3	48.1	30.2
1990	90.7	40.1	20.4	110.4	64.5	38.7
1991	--	29.5	--	29.5	16.4	9.4
1992	--	30.8	--	30.8	16.3	8.9
Total	453.8	164.6	116.3	502.1	321.4	212.5
Portion Attributed to GLIP:				310	200	130

Figure 3-4. Total Projected Benefits From Improved Geothermal Well Logging and Log Interpretation for Discount Rates of 0, 5, and 10% (Change in Slope for 1991 and 1992 Results From Truncation of the Scenario and Does Not Reflect a Real Probability of Lessened Benefits in Those Years.)

to accelerate, these benefits will be very large. The postulated scenario also neglects direct-use applications. In other work (Rigby, et al., 1978), SAI has found that the near-term potential for direct-use development in California may support 400 to 500 production wells. This is equal to something on the order of 10 percent of the electrical development scenario we have used. Although California has much greater potential for direct use than any other western state, the other western states will have some degree of development for direct use. It is clear that logging wells drilled for direct use might increase the estimated benefits by 10 to 20 percent, especially since initiation of direct applications is even more sensitive to drilling risk and investor confidence than is electrical development. Other benefits from improved geothermal log interpretation will occur as a result of application of logged data to improved reservoir management, restoration of injectivity in clogged reinjection wells, stimulation (fracturing) of wells with unsatisfactory flow, and the development of hot dry rock resources. Some of these benefits such as the benefits to reservoir management and hot dry rock will not occur within the time frame of the geothermal scenario we have adopted. Others apply to techniques (such as well stimulation, or direct use applications) which are not yet sufficiently developed to allow a projection of the significance they will have in geothermal development. In any case quantitative estimates of these benefits were not attempted. Therefore, the dollar benefits given in this report do not include these possible applications of geothermal log interpretation.

4.0 DATA PRIORITIES

Having established the magnitude of the research effort that might appropriately be undertaken, it is also desirable to consider implications that the benefit analysis may have for the research program. Geothermal development is a new field of application for well logging, and as a result there is little experience on which to base judgments regarding which lines of research may be the most fruitful. It is useful to examine the value that measurement of various reservoir parameters can have as a means of determining "borehole parameter priorities." The benefit analysis is a useful tool through which to approach this problem. This has already been done to some extent in Section 3.4 where it was concluded that the needs of reservoir modeling and assessment might appropriately be given emphasis early in the program. However, considerably more information can be gained from the benefit analysis.

This section will examine the implications of the benefit analysis regarding borehole data priorities. Cost/benefit analysis can be a useful tool in establishing priorities. It is, however, limited by the simplifying assumptions necessary to achieve a result. Cost/benefit analysis can provide useful input, but it is no replacement for experienced judgement.

4.1 DATA TYPES

Well logging instruments measure a number of properties in a borehole. Problems of interpretation of the resulting measurements can range from correctly applying calibration and correction factors to complex analyses involving the use of several different logs to derive parameters that cannot be directly measured. It is important to draw some distinction between "log data" in the sense of the values of the phenomena actually measured by the tools and "log data" in the sense of formation parameters inferred from the logs.

The phenomena which are most frequently measured by logging instruments include:

- o temperature (in the borehole)
- o pressure (in the borehole)
- o borehole diameter
- o conductivity/resistivity
- o natural radioactivity
- o local variations in electrical potential
- o electron density (measured by gamma ray scattering)
- o acoustic velocity (in some cases both p and s-wave velocities are measured)
- o a variety of measurements associated with neutron cross-sections
- o and many other properties that are, or could be, measured; some entirely inside the borehole, such as flow rate, fluid chemistry, or heterogeneity (presence of bubbles or solids) and some dealing with the formation, such as magnetic properties or acoustic attenuation

Some of these measurements (the diameter of the wellbore, for example) may be used directly in assessing field or well performance or controlling field operations, but the main purpose for most logging is the interpretation of the logs to deduce the parameters that control the performance of a well or a field. These include (Evans, 1970):

- o formation temperature
- o rock type and unit thickness
- o porosity
- o formation damage (skin effect)
- o density
- o permeability

- o fracture characteristics
- o fluid properties (viscosity, heat capacity, etc.)
- o matrix bulk properties (heat capacity, thermal conductivity, compressibility, drillability, etc.)

It is the knowledge of these reservoir parameters that makes possible the realization of the benefits that we have estimated. For example, formation temperature and permeability may be used to determine when a well has been drilled deep enough, or permeability and porosity may be used in aiding the analysis of flow test results. The data priorities that this cost/benefit analysis can illuminate will therefore be for these parameters. Once such priorities are established, experience in log analysis and studies of rock properties and tool responses can be used to select those log analysis strategies that are likely to be most fruitful in contributing to the evaluation of the high priority parameters.

We must also include another class of data that is not entirely comparable to the reservoir parameters we have listed. This is the undisturbed formation properties (drilling alters the properties immediately around the well bore), and the use of these to assess reservoir structure. Properties like undisturbed density, resistivity, and seismic velocity are much more directly related to the logging measurements than parameters like porosity, and relate directly to the measurements made in surface geophysical surveys. Such data might contribute to finding the reservoir limits, thereby aiding modeling and well siting (two of the three largest benefit areas).

4.2 RESERVOIR MODELS

As one approach to determining the importance of various reservoir parameters to reservoir performance and the assessment thereof, we examined the input to representative numerical simulation models. Determining the important input parameters

provides data of a twofold nature. It tells us what parameters are sought by industry for the evaluation of reservoir performance; and, insofar as the models accurately reflect the true performance of geothermal reservoirs, it tells us the most important reservoir parameters.

One model on which data were collected was the reservoir simulation model developed by Phillips Petroleum (Thomas and Pierson, 1978). Reports in the open literature were relied on for information, since Phillips was not prepared to give its model away. Table 4-1 lists the input data for this model. The model provides a three dimensional, multi-phase, finite difference simulation for geothermal reservoirs. The hydrodynamic equations for conservation of mass and energy in porous media flow are solved by an implicit treatment of pressure with an explicit treatment of saturation, using separate mass equations for the liquid and vapor phases. Changes of state are treated at each time step.

In order to prevent the occurrence of oscillations in the calculated values of saturation and pressure for some problems, an implicit numerical treatment is used for the bottom hole production rate and is optional for other variables. This treatment of the production rate, which occurs in the mass balance equation, involves the classical production rate expression:

$$Q = \frac{2\pi kh\rho(p-p_w)}{\mu[\ln(r_e/r_w) + S-1/2]} \quad (4-1)$$

where

Q = production rate

k = permeability

h = formation thickness

ρ = fluid density

P = formation pressure

P_w = pressure in the wellbore
 r_e = external radius
 r_w = radius of the wellbore
 μ = viscosity
 s = skin factor

For two phase flow, k must be modified appropriately (Corey, 1954).

TABLE 4-I PHILLIPS MODEL INPUT PARAMETERS

Parameter
Initial Temperature
Initial Thermal Gradient
Initial Pressure
Initial Water Saturation
Formation Compressibility
Formation Permeability
Formation Porosity
Formation Specific Heat
Formation Thermal Conductivity
Formation Dip
Formation Thickness
Formation Extent
Well Bore Radius
Irreducible Water Saturation
Irreducible Steam Saturation
Skin Factor
Minimum Flowing Pressure
Fluid Viscosity

A model supplied by the Lawrence Berkeley Laboratories designed for the interpretation of interference and production (flow) testing was also examined (Tsang, C.F., 1978). It is an

analytic model based on the line source solution to the diffusion equation for one phase laminar flow in porous media of infinite lateral extent. The model includes well bore storage and skin effects, but does not treat the energy content of the fluids produced at the well. It automates the type-curve analysis used in reservoir engineering to find the permeability-thickness product, the porosity-compressibility-thickness product, the skin effect, and the distance to a barrier boundary. Table 4-II lists model parameters.

TABLE 4-II LBL WELL TEST MODEL PARAMETERS

Parameter
Permeability
Porosity
Compressibility
Fluid Viscosity
Reservoir Thickness
Skin Effect
Distance to Observation Well
Distance to Barrier Boundary

In order to get a better idea of the significance of specific parameters, sensitivity analysis can be applied to some of the most significant equations (it had been hoped to test the Berkeley model under interactive programming conditions to further examine sensitivity, but delays were encountered in obtaining the software). Neglecting skin effect, the steady state radial flow solution for a porous, isotropic medium is:

$$Q = \frac{2\pi kh(p_e - p_w)}{\mu [\ln(r_e/r_w) - 1/2]} \quad (4-2)$$

where

Q = flow rate, cm^3/sec
 k = formation permeability, millidarcys
 h = formation thickness, cm
 p_e = pressure at outer boundary, atm
 p_w = pressure at well radius, atm
 μ = fluid viscosity, centipoise
 r_e = radius of drawdown, cm.
 r_w = well bore radius, cm.

The sensitivity coefficient K_X of a variable X is defined by the equation $\delta Q = K_X \delta X$ where δX and δQ are percentage uncertainties in X and Q . Since the partial derivative can be defined by $\Delta Q \approx (\partial Q / \partial X) \Delta X$ and $\delta Q = \Delta Q / Q$ and $\delta X = \Delta X / X$, the sensitivity coefficient is

$$K_X = (\partial Q / \partial X) (X / Q) \quad (4-3)$$

$$K_k = \frac{\partial Q}{\partial k} \frac{k}{Q} = 1$$

$$K_h = \frac{\partial Q}{\partial h} \frac{h}{Q} = 1$$

$$K_\mu = \frac{\partial Q}{\partial \mu} \frac{\mu}{Q} = -1$$

$$K_{p_e} = \frac{\partial Q}{\partial p_e} \frac{p_e}{Q} = \frac{p_e}{(p_e - p_w)}, \quad K_{p_e} > 1 \quad (4-4)$$

$$K_{p_w} = \frac{\partial Q}{\partial p_w} \frac{p_w}{Q} = - \frac{p_w}{(p_e - p_w)}, \quad K_{p_w} < 0 \text{ and } |K_{p_w}| < 1$$

$$K_{r_e} = \frac{\partial Q}{\partial r_e} \frac{r_e}{Q} = - \frac{1}{\ln \frac{r_e}{r_w} - 1/2}, \quad K_{r_e} < 0 \text{ and } |K_{r_e}| \ll 1$$

$$K_{r_w} = \frac{\partial Q}{\partial r_w} \frac{r_w}{Q} = \frac{1}{\ln \frac{r_e}{r_w} - 1/2} \quad 0 < K_{r_w} \ll 1$$

Figure 4.1 shows a plot of change in flow rate versus change in the variables for a hypothetical case: 160 atm., 40 atm., 1500m meters, and 12 cm for p_e , p_w , r_e , r_w respectively. The highest sensitivity is to the undisturbed formation pressure. This parameter is often obtained from the water level in shut-in wells and need not depend on logged data. A high sensitivity is also shown for viscosity, but it should be kept in mind that while viscosity depends on several factors (chiefly temperature and fluid composition), the range of uncertainty is usually less than that for some other parameters.

Another significant equation is the formula for total heat content in the reservoir. This is, in fact, the first and most basic estimate in any reservoir assessment. For a radial geometry and average temperature, T , the total quantity of heat stored in the fluids of a geothermal reservoir is given by:

$$E = C_{p_w} \phi \rho_w \pi (r_e^2 - r_w^2) hT + C_{p_r} (1-\phi) \rho_r \pi (r_e^2 - r_w^2) hT \quad (4-5)$$

where

- C_{p_w} = specific heat of brine
- C_{p_r} = specific heat of matrix rock
- ϕ = porosity of formation
- ρ_w = density of brine
- ρ_r = density of matrix rock
- r_e = external boundary of reservoir
- r_w = well bore radius
- h = formation thickness
- T = average temperature of brine

The recoverable energy is a fraction of the energy stored, and depends on the production method and surface plant efficiency.

Figure 4-1. Flow Rate Sensitivity Coefficients

p_e is pressure at outer boundary
 k is permeability
 h is formation thickness
 r_w is wellbore radius
 r_e is distance to outer boundary
 p_w is pressure at r_w
 μ is viscosity

The sample case shown is $p_e = 160$ atm., $p_w = 40$ atm.,
 $r_e = 1500$ m, $r_w = 0.12$ m.

The sensitivity coefficients work out as follows:

$$\begin{array}{ll}
 K_h = 1 & 0 < K_{C_{pw}}, K_{\alpha_{pr}} < 1 \\
 K_T = 1 & \\
 K_{r_e} \approx 2 & 0 < K_\phi < 1 \\
 K_{r_w} \approx 0 & 0 < K_{\rho_w}, K_{\rho_r} < 1
 \end{array} \quad (4-6)$$

Figure 4.2 shows these for an example with $C_{pw}=1$ cal/g- $^{\circ}$ C, $\rho_w=1$ g/cm 3 , $S_r=2.5$ g/cm 3 , $C_{pr}=0.2$ cal/g- $^{\circ}$ C, and $\phi=20\%$.

Examining Figures 4-1 and 4-2, it is clear that reservoir structural information, the thickness and lateral dimensions, is extremely important. Permeability and formation temperature also are important, and rock properties will usually dominate water properties (except for viscosity). Porosity does not have a very significant impact in these two cases, but data on porosity may be essential in curve matching for flow test analysis and in interpreting other log data.

4.3 PARTITION OF BENEFITS BY RESERVOIR TYPES

Log interpretation problems vary depending on the nature of the geothermal resource areas. We have already seen that lithologic identification, which can contribute to analysis of reservoir structure and size, as well as helping establish matrix properties such as specific heat, is very important; and it is certainly obvious that this interpretation problem will depend on geology. Another major question is the type of permeability,

Figure 4-2. Energy Content Sensitivity Coefficients

r_e is reservoir radius
 T is reservoir temperature
 h is formation thickness
 c_{pr} is specific heat of the matrix rock
 ρ_r is density of the matrix rock
 c_{pw} is specific heat of the brine
 ρ_w is brine density
 ϕ is porosity

The sample case shown is $C_{pw}=1 \text{ cal/g-}^\circ\text{C}$,
 $\rho_w=1\text{g/cm}^3$, $S_r=2.5\text{g/cm}^3$, $C_{pr}=0.2\text{cal/g-}^\circ\text{C}$, and $\phi=20\%$.

intergranular or fracture dominated. Scientific Software Corporation (SSC) has already defined a rough reservoir classification scheme based on location, geology, temperature, rock type, and salinity (Sanyal, et.al., 1979). Different reservoir conditions can make a difference in the selection of logs and interpretation techniques. The breakdown of the benefit estimate according to the reservoir classification can therefore be of some value in setting research priorities. Breakdowns of the various benefit categories were made but did not differ significantly from one benefit type to another so we shall present only the results for total benefits. Numbers given refer to gross benefits.

SSC's categorization by temperature is as follows:

steam

high temperature $T > 204^{\circ}\text{C}$

medium temperature $149^{\circ}\text{C} < T < 204^{\circ}\text{C}$

low temperature $T < 149^{\circ}\text{C}$

Figure 4-3 shows gross benefits by reservoir temperature class. Information was lacking on a few areas. There is nothing particularly surprising here; reservoir temperatures above 200°C are less common than cooler ones, while temperatures below 150°C are seldom economical for electrical power generation, and few are included in the scenario. A number of the logging instruments available from the logging service industry are rated to 200°C or above. However, there are apparently still problems with log interpretation and tool performance that develop before temperatures reach this level. A more helpful division might be around 175°C . About 25% of the benefit estimate comes from resources with temperatures less than 175°C .

Figure 4-4 shows the breakdown of benefits according to major geologic areas as defined by SSC. The importance of the Basin and Range province is obvious. The large contribution of

Figure 4-3. Benefit Breakdown by Resource Temperature.
(Hatched Portion Indicates Present Value Discounted at 10% Annually)

Figure 4-4. Benefit Breakdown by Major Geologic Provinces. (Hatched Portion Indicates Present Value Discounted at 10% Annually)

the Northwest Volcanic region is worth noting. The MITRE development scenario includes quite a few sites in the Northwest, most of which are anticipated to be developed late in the scenario's time period. It is not clear if this projection will be borne out in practice. At present geothermal electric development activity is focused in California and the Basin and Range area. Figure 4-4 may therefore be a valuable reminder that improved log interpretation may return significant benefits elsewhere as well. Hawaii is also projected to have large scale development late in the scenario. While initial development in Hawaii seems likely to be ahead of the scenario, later development will depend on economic expansion and the possibility of developing means of inter-island energy transfer. Without Federal assistance, the extent to which well logging will be exploited in Hawaii seems questionable since there is no accompanying market for oil and gas logging services.

The classification by lithologic types set up by SSC (Sanyal, et.al., 1979) involved the following:

sedimentary

metamorphic

igneous (crystalline and glassy)

volcanic ash and associated sediments

breccia

hydrothermally altered

The classification scheme allowed an area to have more than one designation to denote mixed formations. This unfortunately is not useful for dividing the benefits among reservoir types. We were therefore forced in several cases to take the expedient of considering only dominant rock type. The "hydrothermally altered" class was dropped although many reservoirs show some degree of alteration. The Salton Sea field was classed as sedimentary, although a case could be made that it is so extensively altered as to be metamorphic.

Figure 4-5 shows the benefit breakdown. Two extra categories are used. So many fields display a mixture of sedimentary rocks with intrusives or volcanics that this type is shown separately. Sites on Northwest volcanoes such as Mt. Hood which are likely to feature a layering of ash and basalts are also shown separately. This should not be confused with the Northwest Volcanic regional classification (in Figure 4-4) which includes more sites.

Figure 4-5 shows that there is no dominant geothermal lithology. The prevalence of mixed formations is a very important feature. These reservoirs can be expected to be very complex. Log interpretation may be very difficult, but other means of investigating the reservoir may also face difficulties. The demand for and benefit from reliable log interpretation in this class of reservoirs may well exceed the estimates we have made here. The high significance of sedimentary formations is also worth noting. Because of the rapid development likely at the Geysers resource, both vapor and liquid dominated, the metamorphic group has a higher discounted value relative to its undiscounted total than do the others. This is indicative of greater expected near-term development.

The classification by pore type bears a somewhat similar message. SSC proposes a classification into sedimentary intergranular, fracture, and vesicular or vuggy pore geometries, but lists no resources exclusively in the third class. We are again faced with reservoirs having a mixture of characteristics. Since the standard porosity measures may be acceptable in rock with vesicular combined with intergranular porosity, we treat these together with the purely intergranular pore type. Figure 4-6 therefore shows benefits for unfractured formations, for fractured, non-porous formations, and for formations having both fractures and intergranular or vesicular/vuggy porosity. The importance of better approaches to fractured systems is obvious. However, it is also clear that porosity and permeability in

Figure 4-5. Benefit Breakdown by Major Rock Types.
(Hatched Portion Indicates Present Value Discounted at 10% Annually)

Figure 4-6. Benefit Breakdown by Pore Geometry.
(Hatched Portion Indicates Present Value
Discounted at 10% Annually)

unfractured reservoirs also deserve attention. The significance of mixed systems is again striking. While adequate determination of permeability from log response is not available for any of the pore types, the formations with fracturing and other porosity are liable to pose special problems. There is likely to be a special need for development of the experience and methodology necessary to separate the permeabilities in such systems. One question that may prove to be of considerable interest and difficulty is the fracture pore volume in a system with a mixture of pore geometries. This datum might be very valuable in interpreting flow tests to determine such things as the extent to which interstitial water is being tapped.

The salinity classification is

- low (<5000 ppm)
- medium (5000 to 35000 ppm)
- high (35000 to 100000 ppm)
- hypersaline (>100000 ppm)

Figure 4-7 shows the benefit breakdown.

4.4 DATA REQUIREMENTS

The types of data required to achieve each of the types of benefits identified must also be looked at. This has already been indicated in the discussion of each benefit in Section 3.3. By looking at the number of benefits to which each datum contributes and by weighting this with consideration of the dollar value estimated for each of the benefit categories involved, an approach can be made estimating the value of the types of data that can be obtained from well logging, although we must not forget that a simple counting of benefit types cannot be substituted for a real understanding of the use that would be made of the data in achieving benefits. Table 4-III lists a set of the parameters discussed in Section 4.1 as data that might be

Figure 4-7. Benefit Breakdown by Salinity. (Hatched Portion Indicates Present Value Discounted at 10% Annually)

Table 4-III. Interaction of Borehole Data with Projected Benefits

Benefit Borehole Parameter						
	Modelling	Well Siting	Well Costs	Reinjection	Flow Testing	Cost of Bad Wells
Flow Rate			x		x	
Fluid Characteristics	x		x			
Fracture Location		x	x	x		x
Fracture Orientation		x	x	x		
Heterogeneity	x			x	x	
Lithology	x	x	x	x	x	
Permeability Porosity	x		x	x	x	x
Temperature and Thermal Conductivity	x	x	x			x
Undisturbed Formation Properties	x	x	x	x		

obtained from logs against the benefit categories estimated. Table 4-III shows the five drilling-related cost savings and "modelling." Improved reservoir modelling is likely to be the major factor in earlier utility commitment and, hence, in the benefit estimated for earlier power-on-line; in addition, better models may contribute to several of the cost reductions, for example, improved drilling success. The five cost reduction benefits are in order of estimated magnitude from left to right. A check is placed opposite the data type under each benefit to which a significant contribution was identified. It would be possible to convert this to a numerical ranking scheme by rank ordering the contributions to each benefit category and using the estimated size of the benefit categories as a weighting factor, but we believe that this would be pushing the approach past its limits of accuracy.

In considering borehole data priorities, account must also be taken of the sensitivity analyses discussed in Section 4.2, especially when considering the contribution of each different datum to reservoir modelling. The reservoir extent, (which gives significance to inter-well correlation and the application of values of undisturbed formation properties in interpreting surface data), was the most important to total energy content, but was less important in flow rate. Formation thickness (which might be found by lithologic identification), was important in both. Permeability ranked high for flow rate.

The analysis of Section 4.2 on the breakdown of benefits by reservoir characteristics is also helpful, since some data has greater significance in some reservoir types than in others. Most obviously, fracture properties will only be of interest in fractured reservoirs. Fracture permeability is obviously a dominant concern for geothermal development, but it is also clear that many reservoirs will have both primary and secondary permeability, and both will have to be dealt with. It is also clear that no particular lithologic type dominates. The impor-

tance of lithologic identification from well logs will probably be greatest in sedimentary and complex, mixed types of reservoirs, and least in the purely igneous reservoirs; but since lithologic corrections are needed to interpret tool response, it will be important everywhere. The value of log data in combination with surface data will vary with reservoir type. The petroleum industry has shown seismic data to be of great value in sedimentary and mixed formations. Gravity (associated with density) data may be of most use in reservoirs with intergranular porosity, since these are most subject to densification and compaction. Electrical properties may come to the fore in reservoirs in which faulting is of great importance and matrix resistivity is high, such as Basin and Range type igneous reservoirs. On the other hand, electrical surveys are of little use on highly saline resources.

Finally, we should consider the concerns of those actively involved in using log data in the development process. Since geothermal development is in its infancy, the extent of experience that any particular individual has with different types of reservoirs is limited. In our contacts with people involved in geothermal resource development we found that each individual's perception was strongly colored by the problems with which he was currently dealing. All were aware of this and were quick to point out that their needs depended strongly on the reservoir types with which they were then dealing. Because of their immediacy, problems of drilling control and exploration received considerable attention. Fracture permeability or at least location was mentioned most often, although some emphasis was also given to intergranular permeability by those whose resources had it. Formation temperature and then lithologic identification were next mentioned most often. The value of undisturbed formation properties for geophysical modeling was recognized, but the extent to which an effort was made to relate log data and surface data was highly variable. The value of knowing the dominant fracture orientation was also mentioned.

Considering, then, the benefits we have estimated, the contributions that various data can make to them, and the distribution of benefits among reservoir types, it is possible to make a rough estimate of borehole data priorities. Lithologic interpretation would seem to be of first importance because of its wide spectrum of applications. However, "lithologic identification" is a nice and simple phrase but actually conceals a wide range of investigations. Closely following lithology, we would place permeability, if an accurate, log-based permeability measurement can be made for all reservoir types. If permeability must be approached through a horde of measurements, some for fractures and some not, then we would regard it as more reasonable to treat these separately and to give each a lower priority. Whether or not techniques for finding permeability from logs can be found is a difficult question. Nuclear magnetic logging (Brown, 1969) has been put forward as a possibility. Better determination of the depth of filtrate invasion into the formation might be another approach. Third priority may be assigned to the assessment of undisturbed formation properties. Even more than for lithologic analysis, however, it should be recognized that in some ways this is several topics rather than one. Fracture location and porosity measurement are of similar importance and rank fourth if direct measurement of permeability is not achieved. Since part of the problem to be dealt with in regard to porosity is distinguishing primary and secondary porosity, fracture location might be regarded as a prerequisite. Logs for the formation temperature and/or evaluation of thermal conductivity from logged data, which can aid formation temperature and heat flow calculation, rank next. Quick determination of formation temperature during drilling is of special value in exploratory drilling. And we would follow these priorities with fracture orientation, heterogeneity of borehole fluid, flow rate, and fluid characteristics. These last three are logs for use in flowing wells and are thus different from the geophysical logs; much of their value is in plant and field management, although flow rate and temperature logs can be used in some cases to locate fractures.

5.0 ROLE OF LOGGING AND LOG INTERPRETATION IN GEOTHERMAL DEVELOPMENT

In setting priorities for research in geothermal well logging, it should be kept in mind that wireline logging is not the only means of gaining downhole information. Lithologic interpretation, for example, can be made from the drill cuttings collected during drilling. This is not so satisfactory as logging because exact transitions and the placement of thin layers may be obscured because the cuttings do not reach the surface in perfect sequence. Also structural properties of the rock will obviously be obscured. In fairly massive or homogeneous formations, however, the cuttings record may be sufficient. Coring can return a better sample with structural features retained. Coring is difficult and expensive, and the core may be altered by removal (pressure changes and the loss of the original pore fluid, for example), but it can be measured in a laboratory with great precision. Perhaps, the greatest drawback of coring is that it yields a very limited sample, in both the horizontal and vertical dimensions. The drilling record can also yield information on fracture location. Changes in drilling rate, the appearance of characteristic mineralization, and loss of circulation can all be indicators of fractures. None of these, however, are universal indicators, nor is the vertical control so obtained very exact.

Flow testing is another important means of obtaining information. There is no escaping the simple fact that the best way to assess the performance of a well is by allowing it to perform. Flow tests are most significant for permeability and temperature, but data can also be obtained on porosity, interval thickness, reservoir volume, and inter-well communication. Flow tests are time consuming and require at least some initial

downhole data for interpretation. Flow testing with two phase flow is a process with which there is considerably less experience than there is with pumping tests.

The reasons for wireline logging, therefore, stem not so much from the uniqueness of the data as from more relative considerations, specifically timing, accuracy, and cost. Log data, at least qualitatively, can be available during or immediately following drilling. In this it is unlike either laboratory or flow test results and can be available for decisions on subjects such as drilling control and well completion. The superior accuracy of wireline logging is most closely related to superior vertical control and to the fact that measurements are made in situ. Cost, of course, relates to the relative costs of logging, drilling, coring, and testing wells.

Logging exists as part of a data inputs complex that interact in the process of creating a valid analysis of a geothermal reservoir. Logging is by far the most versatile, fastest, and cheapest means of obtaining subsurface data. But, a great portion of its value in geothermal work, much more than is the case in the petroleum industry, lies in its use in conjunction with other data. Log data can provide essential input to reservoir modeling, geophysical analysis, and interpretation of flow tests. It is unlikely, for example, logging is going to be developed to such a level that it will eliminate the need to test a well after drilling. On the other hand, good determination of some parameters from logs can greatly increase the accuracy and ease with which flow test results can be used.

The experience of the utility of logs that is available to guide practice in the geothermal drilling is at present mainly carried over from petroleum operations. But, the geologic and economic conditions are radically different. The petroleum industry enjoys a handy separation of the operations of exploration, drilling, and reservoir engineering. Logging is important

to the drilling operation; and after drilling is completed, a key assessment can be made of the presence, quantity, and recoverability of hydrocarbons. The conditions of geothermal development are radically different. Unlike hydrocarbons, geothermal energy cannot be easily stored or transported. A geothermal well is of no value unless a massive additional investment is made in building surface facilities to use the geothermal energy at, or near, the site of the well. The need to reinject the great volumes of fluid produced adds an additional complication. A geothermal resource cannot generate income until it is well enough understood to justify a high level of investment. An added burden is placed on exploration since we must establish not only the existence of a resource, but also that the particular area in which a surface plant is to be built has enough potential to support the plant for its useful life. At the same time due to the temperature and geology, geothermal wells often cost two or three times as much as petroleum wells of the same depth. As a result, the view of drilling as a means of reservoir investigation changes. Long-term flow testing also becomes a liability when the product cannot be easily stored or transported for sale elsewhere.

Overall, geothermal resource investigation differs from the situation for petroleum in that projecting performance becomes paramount, while merely establishing the presence and quantities of pore fluid is far less significant. Simultaneously, the significance of timing changes. The entire process of finding and investigating a geothermal resource becomes a unitary process that must all be carried out before a return on investment is possible. The greater complexity of geothermal formations places greater value on all forms of subsurface information. Logging and log interpretation should take on a greatly expanded role in this process because of the changes in relative costs and the importance of time. However, the techniques must be applied before they can have value.

These findings lead to the conclusion that well logging is liable to be severely under-utilized in geothermal development, to the continuing detriment of the geothermal energy program, unless a clear perception is developed of the different role that logging should have in geothermal development as opposed to petroleum operations. The unsatisfactory temperature performance of logging tools is, of course, limiting applications at present, but both government and industry are moving to change this. However, the acquisition of log data will continue to be restricted unless logging is recognized as not just part of the drilling program but also as an integral part of exploration and reservoir engineering.

APPENDIX A

The geothermal development scenario used in this study was that developed by the MITRE Corporation for the U.S. Department of Energy. The scenario estimates drilling activity through 1990 and resulting power-on-line through 1992 at 30 geothermal prospects in the western United States. The scenario assumes that exploration drilling must occur 4 years prior to power-on-line and production and reinjection drilling, 2 years before power-on-line. This explains the use of the power-on-line scenario through 1992. Since the study deals with some benefits that are associated with the power plant and some associated with the well drilling, it was decided that to maintain balance all power plants with production drilling projected up to 1990 should be included, requiring extension of the power-on-line scenario to 1992 (the drilling scenario also includes exploratory wells in 1989 and 1990 which would be for power plants that would not be completed until still later, but this represents a very minor effect on the benefit totals). The drilling scenario also includes replacement production wells assumed to be required to make up for cooled or damaged wells. These are calculated as 10% of total operating production wells (those associated with power plants that have begun operation) per year for liquid-dominated resources. Half this rate was used for the Geysers steam field. The scenario does not include replacement of clogged reinjection wells, which may be a serious flaw, and one that may neglect an important application of well logging, control of treatment programs to restore or maintain injectivity in clogged wells. Exploration, production, and replacement wells were all assumed to bear the same cost, while reinjection well costs differed in a few cases. Table A-I which is the same as Table 3-I in the main body of the report, lists the areas and well costs. Tables A-II through A-VI give the scenarios for power-on-line and the four well types.

Table A-I. Resource Areas for the Assumed Development Scenario

(Temperature data is not available for the liquid-dominated (hydro) resource at the Geysers and the West Yellowstone area)

Site	Temperature (°C)	Depth (KM)	Well Prices (\$K)	
			Production	Reinjection
Geysers (Steam), CA	240	2.5	1214.	1214.
Salton Sea, CA	340	1.5	484.	484.
Valles Caldera, NM	240	1.5	1191.	1191.
Brady, NV	214	1.0	794.	794.
Brawley, CA	260	2.0	484.	484.
Roosevelt, UT	280	1.3	645.	645.
Beowawe, NV	240	1.5	1191.	1191.
Coso, CA	220	1.5	744.	744.
Mono-Long Valley, CA	220	1.5	744.	744.
Cove Fort/Sulfurdale, UT	200	2.0	1843.	1228.
Heber, CA	190	1.5	726.	484.
Geysers (Hydro), CA	--	2.5	1331.	1331.
East Mesa, CA	180	1.5	726.	484.
Steamboat, NV	210	0.8	397.	397.
Surprise Valley, CA	170	1.5	1117.	744.
Chandler, AZ	178	2.5	2070.	1379.
Leach, NV	170	2.5	2587.	1725.
Bruneau-Grandview, ID	200	2.5	2587.	1725.
Lassen, CA	240	1.5	744.	744.
Alvord, OR	200	2.0	2949.	1966.
Safford, AZ	200	2.5	2587.	1725.
Weiser/Crane Creek, ID	160	1.5	1117.	744.
Vale, OR	160	1.5	715.	477.
Thermo, UT	200	2.0	1475.	988.
Raft River, ID	140	2.0	1101.	734.
Glass Mountain, CA	210	2.5	1725.	1725.
Puna, HI	275	2.5	2760.	2760.
Mount Hood, OR	125	1.5	893.	595.
Baker Hot Springs, WA	165	2.5	2587.	1725.
W. Yellowstone, MT	--	2.5	1104.	1104.

Table A-II. Power On-Line Scenario (MW)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
GEYSERS (STEAM), CA	190.	275.	165.	275.	160.	220.	110.	0.	0.	0.	0.	0.	0.	0.
SALTUN SEA, CA	0.	0.	0.	0.	50.	0.	100.	75.	75.	100.	100.	100.	100.	100.
VALLES CALDERA, NM	0.	0.	0.	0.	50.	0.	0.	100.	0.	100.	0.	100.	100.	100.
BRADY, NV	0.	0.	0.	0.	50.	0.	0.	50.	0.	100.	0.	100.	100.	100.
BRAWLEY, CA	0.	0.	0.	0.	50.	0.	50.	0.	100.	100.	100.	100.	100.	100.
ROOSEVELT, UT	0.	0.	0.	0.	50.	0.	0.	50.	0.	50.	0.	100.	100.	100.
DEOWAVE, NV	0.	0.	0.	0.	50.	0.	0.	50.	0.	50.	0.	100.	100.	100.
COSO, CA	0.	0.	0.	0.	0.	0.	50.	50.	50.	150.	150.	150.	0.	0.
MONO-LONG VALLEY, CA	0.	0.	0.	0.	0.	0.	50.	0.	100.	0.	0.	100.	0.	0.
COVE FORT/SULFURDALE, UT	0.	0.	0.	0.	0.	0.	50.	0.	50.	0.	50.	50.	100.	100.
HEBER, CA	0.	0.	0.	0.	0.	0.	50.	0.	50.	0.	100.	100.	100.	100.
GEYSERS (HYDRO), CA	0.	0.	0.	0.	0.	0.	100.	100.	100.	100.	100.	100.	100.	100.
EAST MESA, CA	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	0.	0.	0.	0.
STEAMBOAT, NV	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	0.	100.	0.	0.
SURPRISE VALLEY, CA	0.	0.	0.	0.	0.	0.	0.	50.	0.	50.	100.	100.	100.	100.
CHANDLER, AZ	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	0.	100.	50.	0.
LEACH, NV	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	100.	100.
BRUNEAU-GRANDVIEW, ID	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	100.	100.	100.
LASSEN, CA	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	0.	0.
ALVORD, OR	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	50.	50.
SAFFORD, AZ	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	50.	0.	0.
WEISER/CRAVE CREEK, ID	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	0.	0.	0.
VALE, OR	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	100.	100.	100.
THERMO, UT	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	50.	50.	50.
RAFT RIVER, ID	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.	0.	100.
GLASS MOUNTAIN, CA	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	50.	0.	0.
PUNA, HI	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.
MOUNT HOOD, OR	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	100.	200.	200.
BAKER HOT SPRINGS, WA	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.
W. YELLOWSTONE, MT	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	50.	0.	0.
TOTALS	190.	275.	165.	275.	460.	220.	660.	575.	775.	1100.	700.	2150.	1650.	1700.

Table A-III. Drilling Scenario for Exploratory Wells (Number of Wells)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	TOTAL
GEYSERS (STEAM), CA	5.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0
SALTON SEA, CA	0.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	50.0
VALLES CALDERA, NM	0.0	0.0	0.0	5.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
BRADY, NV	0.0	0.0	0.0	5.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
BRAWLEY, CA	0.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	45.0
ROOSEVELT, UT	0.0	0.0	0.0	5.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
BEOWAWE, NV	0.0	0.0	0.0	5.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
COSO, CA	0.0	10.0	0.0	5.0	5.0	5.0	5.0	5.0	0.0	0.0	0.0	0.0	35.0
MONO-LONG VALLEY, CA	0.0	10.0	0.0	0.0	5.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	20.0
COVE FORT/SULFURDALE, UT	0.0	10.0	0.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	45.0
HEBER, CA	0.0	0.0	0.0	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	35.0
GEYSERS (HYDRO), CA	0.0	5.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	50.0
EAST MESA, CA	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0
STEAMBOAT, NV	0.0	10.0	0.0	0.0	0.0	5.0	0.0	5.0	0.0	0.0	0.0	0.0	20.0
SURPRISE VALLEY, CA	0.0	0.0	10.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	45.0
CHANDLER, AZ	0.0	0.0	10.0	0.0	0.0	0.0	0.0	5.0	5.0	0.0	0.0	0.0	20.0
LEACH, NV	0.0	0.0	0.0	10.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
BRUNEAU-GRANDVIEW, ID	0.0	0.0	0.0	10.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
LASSEN, CA	0.0	0.0	0.0	10.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	15.0
ALVORD, OR	0.0	0.0	0.0	10.0	0.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
SAFFORD, AZ	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0
WEISER/CRAVE CREEK, ID	0.0	0.0	0.0	0.0	10.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
VALE, OR	0.0	0.0	0.0	0.0	10.0	0.0	0.0	5.0	5.0	5.0	5.0	5.0	35.0
THERMO, UT	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	5.0	5.0	5.0	25.0
RAFT RIVER, ID	0.0	0.0	0.0	0.0	5.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	10.0
GLASS MOUNTAIN, CA	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0
PUNA, HI	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	5.0	5.0	5.0	5.0	30.0
MOUNT HOOD, OR	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0
BAKER HOT SPRINGS, WA	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0
W. YELLOWSTONE, MT	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	10.0
TOTALS	5.0	50.0	35.0	85.0	70.0	55.0	85.0	105.0	85.0	85.0	85.0	85.0	830.0

Table A-IV. Drilling Scenario for Production Wells (Number of Wells)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	TOTAL
GEYSERS (STEAM), CA	33.0	55.0	32.0	44.0	22.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	186.0
SALTON SEA, CA	0.0	0.0	4.0	0.0	8.0	6.0	6.0	8.0	8.0	8.0	8.0	8.0	64.0
VALLES CALDERA, NM	0.0	0.0	11.0	0.0	0.0	22.0	0.0	22.0	0.0	22.0	22.0	22.0	121.0
BRADY, NV	0.0	0.0	15.0	0.0	0.0	15.0	0.0	30.0	0.0	30.0	30.0	30.0	150.0
BRAWLEY, CA	0.0	0.0	6.0	0.0	6.0	0.0	12.0	12.0	12.0	12.0	12.0	12.0	84.0
ROOSEVELT, UT	0.0	0.0	7.0	0.0	0.0	7.0	0.0	7.0	0.0	14.0	14.0	14.0	63.0
BEOWAWE, NV	0.0	0.0	11.0	0.0	0.0	11.0	0.0	11.0	0.0	22.0	22.0	22.0	99.0
COSO, CA	0.0	0.0	0.0	0.0	14.0	14.0	14.0	42.0	42.0	0.0	0.0	0.0	168.0
MONO-LONG VALLEY, CA	0.0	0.0	0.0	0.0	14.0	0.0	28.0	0.0	0.0	28.0	0.0	0.0	70.0
COVE FORT/SULFURDALE, UT	0.0	0.0	0.0	0.0	13.0	0.0	13.0	0.0	13.0	13.0	26.0	26.0	104.0
HEBER, CA	0.0	0.0	0.0	0.0	16.0	0.0	16.0	0.0	32.0	32.0	32.0	32.0	160.0
GEYSERS (HYDRO), CA	0.0	0.0	0.0	0.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	240.0
EAST MESA, CA	0.0	0.0	0.0	0.0	19.0	0.0	0.0	19.0	0.0	0.0	0.0	0.0	38.0
STEAMBOAT, NV	0.0	0.0	0.0	0.0	16.0	0.0	0.0	16.0	0.0	32.0	0.0	0.0	64.0
SURPRISE VALLEY, CA	0.0	0.0	0.0	0.0	0.0	21.0	0.0	21.0	42.0	42.0	42.0	42.0	210.0
CHANDLER, AZ	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	40.0	20.0	0.0	80.0
LEACH, NV	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.0	0.0	24.0	48.0	48.0	144.0
BRUNEAU-GRANDVIEW, ID	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	26.0	26.0	26.0	91.0
LASSEN, CA	0.0	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	11.0	0.0	0.0	22.0
ALVORD, OR	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	13.0	13.0	13.0	52.0
SAFFORD, AZ	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	13.0
WEISER/CRAVE CREEK, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.0	0.0	60.0	60.0	60.0	210.0
VALE, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.0	0.0	30.0	30.0	30.0	120.0
THERMO, UT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	0.0	26.0	39.0
RAFT RIVER, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	55.0	0.0	55.0	0.0	0.0	110.0
GLASS MOUNTAIN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0	0.0	0.0	17.0
PUNA, HI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.0	32.0	32.0	80.0
MOUNT HOOD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0	50.0
BAKER HOT SPRINGS, WA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.0	0.0	0.0	27.0
W. YELLOWSTONE, MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0	50.0
TOTALS	33.0	55.0	86.0	44.0	158.0	146.0	193.0	346.0	179.0	746.0	467.0	473.0	2926.0

Table A-V. Drilling Scenario for Reinjection Wells (Number of Wells)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	TOTAL
GEYSERS (STEAM), CA	3.3	5.5	3.2	4.4	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.6
SALTON SEA, CA	0.0	0.0	3.0	0.0	6.0	4.5	4.5	6.0	6.0	6.0	6.0	6.0	48.0
VALLES CALDERA, NM	0.0	0.0	5.0	0.0	0.0	10.0	0.0	10.0	0.0	10.0	10.0	10.0	55.0
BRADY, NV	0.0	0.0	7.0	0.0	0.0	7.0	0.0	14.0	0.0	14.0	14.0	14.0	70.0
BRAWLEY, CA	0.0	0.0	4.0	0.0	4.0	0.0	8.0	8.0	8.0	8.0	8.0	8.0	56.0
ROOSEVELT, UT	0.0	0.0	6.0	0.0	0.0	6.0	0.0	6.0	0.0	12.0	12.0	12.0	54.0
BEOWAVE, NV	0.0	0.0	5.0	0.0	0.0	5.0	0.0	5.0	0.0	10.0	10.0	10.0	45.0
COSO, CA	0.0	0.0	0.0	0.0	6.0	6.0	6.0	18.0	18.0	18.0	0.0	0.0	72.0
MONO-LONG VALLEY, CA	0.0	0.0	0.0	0.0	6.0	0.0	12.0	0.0	0.0	12.0	0.0	0.0	30.0
COVE FORT/SULFURDALE, UT	0.0	0.0	0.0	0.0	6.0	0.0	6.0	0.0	6.0	6.0	12.0	12.0	48.0
HEBER, CA	0.0	0.0	0.0	0.0	7.0	0.0	7.0	0.0	14.0	14.0	14.0	14.0	70.0
GEYSERS (HYDRO), CA	0.0	0.0	0.0	0.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	80.0
EAST MESA, CA	0.0	0.0	0.0	0.0	8.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	16.0
STEAMBOAT, NV	0.0	0.0	0.0	0.0	7.0	0.0	0.0	7.0	0.0	14.0	0.0	0.0	28.0
SURPRISE VALLEY, CA	0.0	0.0	0.0	0.0	0.0	9.0	0.0	9.0	18.0	18.0	18.0	18.0	90.0
CHANDLER, AZ	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	16.0	8.0	0.0	32.0
LEACH, NV	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	10.0	20.0	20.0	60.0
BRUNEAU-GRANDVIEW, ID	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	12.0	12.0	12.0	42.0
LASSEN, CA	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	5.0	0.0	0.0	10.0
ALVORD, OR	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	6.0	6.0	6.0	24.0
SAFFORD, AZ	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	6.0
WEISER/CRAVE CREEK, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0	24.0	24.0	24.0	84.0
VALE, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	0.0	12.0	12.0	12.0	48.0
THERMO, UT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	12.0	18.0
RAFT RIVER, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.0	0.0	21.0	0.0	0.0	42.0
GLASS MOUNTAIN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0	0.0	7.0
PUNA, HI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	16.0	16.0	40.0
MOUNT HOOD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.0	0.0	0.0	22.0
BAKER HOT SPRINGS, WA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	11.0
W. YELLOWSTONE, MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.0	0.0	0.0	22.0
TOTALS	3.3	5.5	33.2	4.4	62.2	65.5	86.5	152.0	80.0	328.0	212.0	216.0	1248.6

Table A-VI. Drilling Scenario for Replacement Wells (Number of Wells)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	TOTAL
GEYSERS (STEAM), CA	7.9	10.6	12.3	15.0	16.7	18.8	20.0	20.0	20.0	20.0	20.0	20.0	201.1
SALTON SEA, CA	0.0	0.0	0.0	0.0	0.4	0.4	1.2	1.8	2.4	3.2	4.0	4.8	18.2
VALLES CALDERA, NM	0.0	0.0	0.0	0.0	1.1	1.1	1.1	3.3	3.3	5.5	5.5	7.7	28.6
BRADY, NV	0.0	0.0	0.0	0.0	1.5	1.5	1.5	3.0	3.0	6.0	6.0	9.0	31.5
BRAWLEY, CA	0.0	0.0	0.0	0.0	0.6	0.6	1.2	1.2	2.4	3.6	4.8	6.0	20.4
ROOSEVELT, UT	0.0	0.0	0.0	0.0	0.7	0.7	0.7	1.4	1.4	2.1	2.1	3.5	12.6
BEOWAWE, NV	0.0	0.0	0.0	0.0	1.1	1.1	1.1	2.2	2.2	3.3	3.3	5.5	19.8
COSO, CA	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.8	4.2	8.4	12.6	16.8	46.2
MONO-LONG VALLEY, CA	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.4	4.2	4.2	4.2	7.0	22.4
COVE FORT/SULFURDALE, UT	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	2.6	2.6	3.9	5.2	16.9
HEBER, CA	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6	3.2	3.2	6.4	9.6	25.6
GEYSERS (HYDRO), CA	0.0	0.0	0.0	0.0	0.0	0.0	3.0	6.0	9.0	12.0	15.0	18.0	63.0
EAST MESA, CA	0.0	0.0	0.0	0.0	0.0	0.0	1.9	1.9	1.9	3.8	3.8	3.8	17.1
STEAMBOAT, NV	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6	1.6	3.2	3.2	6.4	17.6
SURPRISE VALLEY, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.1	4.2	8.4	12.6	29.4
CHANDLER, AZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	2.0	2.0	6.0	14.0
LEACH, NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.4	2.4	4.8	12.0
BRUNEAU-GRANDVIEW, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	1.3	3.9	7.8
LASSEN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	1.1	2.2	5.5
ALVORD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	1.3	2.6	6.5
SAFFORD, AZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	1.3	1.3	5.2
WEISER/CRAVE CREEK, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0	9.0	15.0
VALE, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0	6.0	12.0
THERMO, UT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	1.3	3.9
RAFT RIVER, ID	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	5.5	11.0	22.0
GLASS MOUNTAIN, CA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.7
PUNA, HI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.6
MOUNT HOOD, OR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0
BAKER HOT SPRINGS, WA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	2.7
W. YELLOWSTONE, MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0
TOTALS	7.9	10.6	12.3	15.0	22.0	24.2	39.0	53.6	72.9	107.5	125.4	200.0	690.3

APPENDIX B

In this appendix we shall present a brief example of the calculation of the benefit estimates. The five classes of benefits related to field development costs are all related to the estimated costs of wells for the sites of development assumed in the scenario. Table A-I in the previous appendix lists these values. Four types of drilling are considered in the scenario -- exploration wells, production wells, replacement of old production wells, and reinjection wells. Tables A-III through A-VI give the projections. A projection of total drilling cost for each year can easily be arrived at by multiplying the drilling scenario for each well type by the appropriate well cost for each site. Table B-I presents the total drilling cost which results. It should be pointed out that the drilling scenario apparently makes no allowance for unsuccessful production or reinjection wells. MITRE arrived at the production and reinjection scenarios on the basis of an estimate of the brine flow rate required for a power plant at each site. The replacement well scenario is based on a percentage in each year of the active producing wells (with a two year lag to account for power plant construction) which is taken simply as a running total of the production well scenario. The scenario therefore really gives a lower bound on drilling costs. However, since this cost/benefit study was intended to be consistent with the MITRE scenario, SAI did not make adjustments to allow for failure rate except in one particular, the estimate of a benefit due to improved drilling success. Since this is potentially one of the most significant benefits that may result from the improved knowledge of reservoir structure that will be obtained with better log interpretation, it could not be ignored.

Annual summaries of oil and gas drilling in Oil and Gas Journal were compared with the results for geothermal wells given in Geothermal Energy Magazine and other sources (USGS, 1978).

Table B-I. Total Drilling Costs (10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAD), CA	89.73	92.45	63.74	77.03	49.59	22.88	24.22	24.22	24.22	24.22	24.22	24.22
SALTON SEA, CA	0.00	0.00	5.81	2.42	9.39	7.70	8.08	10.07	10.36	10.74	11.13	11.52
VALLES CALDERA, NM	0.00	0.00	19.66	5.93	1.31	48.38	1.31	48.00	9.89	50.62	50.62	53.24
BRADY, NV	0.00	0.00	17.47	3.97	1.19	22.63	1.19	41.29	6.33	43.67	43.67	46.03
BRADLEY, CA	0.00	0.00	7.26	0.00	7.55	2.71	12.68	12.68	13.26	13.84	14.42	15.00
ROOSEVELT, UT	0.00	0.00	8.39	3.23	0.45	12.06	0.45	12.51	4.13	21.35	21.35	22.25
BEOWAWE, NV	0.00	0.00	19.06	5.93	1.31	26.32	1.31	27.63	8.58	48.00	48.00	50.62
COSO, CA	0.00	7.44	0.00	3.72	18.60	18.60	19.64	50.44	47.76	50.89	9.37	12.50
MONO-LONG VALLEY, CA	0.00	7.44	0.00	0.00	18.60	0.00	30.80	4.76	3.12	32.88	3.12	5.21
COVE FORT/SULFURDALE, UT	0.00	18.43	0.00	0.00	40.54	0.00	42.94	11.61	43.33	43.33	79.06	81.45
HEBER, CA	0.00	0.00	0.00	0.00	18.63	0.00	19.80	4.79	35.96	35.96	38.28	40.61
GEYSERS (HYDRO), CA	0.00	6.90	0.00	6.90	62.14	62.14	66.29	70.43	74.57	78.72	82.86	87.00
EAST MESA, CA	0.00	0.00	0.00	0.00	17.67	3.63	1.38	19.05	1.38	2.76	2.76	2.76
STEAMBOAT, NV	0.00	3.97	0.00	0.00	9.13	1.98	0.64	11.75	0.64	19.53	1.27	2.54
SURPRISE VALLEY, CA	0.00	0.00	11.17	0.00	0.00	35.74	5.58	38.08	68.24	70.58	75.27	79.97
CHANDLER, AZ	0.00	0.00	20.70	0.00	0.00	52.43	0.00	14.49	14.49	109.00	56.57	12.42
LEACH, NV	0.00	0.00	0.00	25.87	0.00	0.00	79.34	12.94	19.14	98.48	177.82	184.03
BRUNEAU-GRANDVIEW, ID	0.00	0.00	0.00	25.87	0.00	0.00	43.98	12.94	16.30	104.26	104.26	110.99
LASSER, CA	0.00	0.00	0.00	7.44	0.00	0.00	11.90	3.72	0.82	12.72	0.82	1.64
ALYDOR, OR	0.00	0.00	0.00	29.49	0.00	0.00	50.13	14.75	18.58	68.71	68.71	72.53
SAFFORD, AZ	0.00	0.00	0.00	25.87	0.00	0.00	43.98	0.00	3.36	3.36	3.36	3.36
WEISER/CRAVE CREEK, ID	0.00	0.00	0.00	0.00	11.17	0.00	0.00	48.02	5.58	93.81	93.81	100.51
VALE, OR	0.00	0.00	0.00	0.00	7.15	0.00	0.00	30.73	3.58	32.89	32.89	35.04
THERMO, UT	0.00	0.00	0.00	0.00	14.75	0.00	0.00	25.07	0.00	9.29	9.29	59.44
RAFT RIVER, ID	0.00	0.00	0.00	0.00	5.50	0.00	0.00	81.47	0.00	82.02	6.06	12.11
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	17.23	0.00	0.00	41.40	0.00	2.93
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	27.60	0.00	13.00	80.04	146.28	150.70
MOUNT BOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	8.93	0.00	0.00	57.74	0.00	4.46
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	25.87	0.00	0.00	88.82	0.00	6.98
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	11.04	0.00	0.00	79.49	0.00	5.52
TOTALS	89.73	136.63	172.64	223.72	294.69	314.21	556.34	631.46	449.44	1511.16	1205.29	1297.62

Failure rate for production oil and gas wells in recent years is about 22 to 23%. The record for geothermal drilling in the U.S. is, of course, much more limited. Drilling in areas where the geothermal resource is well established displays a failure rate on the order of 25 to 27%. Yet at present, only the most obvious, extensive, and accessible geothermal areas are even being investigated, while the oil and gas industry has long ago developed the shallowest and most easily found resources. This is illustrated by the fact that, while the failure rate for oil and gas exploratory drilling is 75 to 85%, the failure rate of drilling to explore new geothermal areas (in the U.S.) is only about 50%.

Better knowledge of reservoir structure and limits can reduce the failure rate for geothermal drilling. More than one Federal research program may help to achieve this goal, but the GLIP can play a major role. A 10% reduction in the failure rate, i.e., a reduction of 2.5 percentage points, (10% of a 25 percentage point failure rate) was judged to be possible in the failure rate for production and replacement wells based on better log interpretation. As a percentage of the successful production wells tabulated in the scenario, this is a 3% savings. The change in failure rate for exploration wells will not be so large, since log data cannot be had for an area that has not been drilled. However, in an area where some wells have been drilled log data may assist further exploration. The potential reduction in failure rate was therefore taken to be only 4% or a savings of 2 percentage points.

These savings were applied to the drilling scenario. It was not assumed that the benefits would be realized immediately but rather that they would be achieved as the result of an eight year program. The GLIP is already encouraging increased logging in some areas and provides two calibration wells. One-eighth of the estimated savings were assumed for 1979, and an additional eighth in each subsequent year until the full benefit was

achieved. Tables B-II through B-IV show the way the benefits work out for exploratory, production, and replacement wells; no benefits were calculated for reinjection wells, since selection of sites for reinjection wells will require different information that may not be provided from logging in geothermal conditions. The 1979 present value can be calculated from the annual sums using selected discount rates.

The other benefits were calculated similarly. The estimate for reduced well costs was the same magnitude as the reduced failure rate. There was a general consensus among those with whom the problem was discussed (Appendix C) that savings of at least a few percent were possible and that in some areas savings might be much greater if drilling depths were reduced by identifying dominant fracture orientations or by logging to establish when a well had reached a satisfactory temperature and permeability. For reduced reinjection, savings applied only to reinjection wells; the estimate being 5%. Reduced expenditures on bad exploratory wells were applied only to exploration wells obviously. Savings of different magnitudes in percentages of the total number of wells were assumed, working out to an average savings of about 4 1/2% per well.

Reduced flow testing was somewhat different. Flow testing was estimated to cost about \$3,000 per day. A savings estimate of one week for production wells and four days for replacement wells was used, and the sums multiplied by the number of wells. Logging costs were calculated similarly.

The benefit from accelerating power on-line was calculated from the power-on-line scenario, Table A-II. It was assumed that the acceleration occurred at the initiation of the first plant on each resource (three years prior to first power-on-line) and that the entire development of the resource was advanced by this amount. This is very conservative since it ignores the fact that some resources may have plants built by

Table B-II. Savings Due to Improved Drilling Success for Exploratory Wells
(10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
CEYSERS (STEAD), CA	0.02	0.03	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SALTON SEA, CA	0.00	0.00	0.02	0.02	0.03	0.04	0.04	0.05	0.03	0.05	0.05	0.05
VALLES CALDERA, NM	0.00	0.00	0.00	0.06	0.00	0.09	0.00	0.12	0.12	0.12	0.12	0.12
BRADY, NV	0.00	0.00	0.00	0.04	0.00	0.06	0.00	0.08	0.08	0.08	0.08	0.08
BRAWLEY, CA	0.00	0.00	0.02	0.00	0.03	0.04	0.04	0.05	0.03	0.05	0.05	0.05
ROOSEVELT, UT	0.00	0.00	0.00	0.03	0.00	0.05	0.00	0.06	0.06	0.06	0.06	0.06
BEOWAVE, NV	0.00	0.00	0.00	0.06	0.00	0.09	0.00	0.12	0.12	0.12	0.12	0.12
COSO, CA	0.00	0.04	0.00	0.04	0.05	0.06	0.07	0.07	0.00	0.00	0.00	0.00
MONO-LONG VALLEY, CA	0.00	0.04	0.00	0.00	0.05	0.00	0.00	0.07	0.00	0.00	0.00	0.00
COVE FORT/SULFURDALE, UT	0.00	0.09	0.00	0.00	0.12	0.00	0.16	0.18	0.18	0.18	0.18	0.18
HEBER, CA	0.00	0.00	0.00	0.00	0.05	0.00	0.06	0.07	0.07	0.07	0.07	0.07
CEYSERS (HYDRO), CA	0.00	0.03	0.00	0.07	0.09	0.10	0.12	0.14	0.14	0.14	0.14	0.14
EAST MESA, CA	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
STEAMBOAT, NV	0.00	0.02	0.00	0.00	0.00	0.03	0.00	0.04	0.00	0.00	0.00	0.00
SURPRISE VALLEY, CA	0.00	0.00	0.08	0.00	0.00	0.08	0.10	0.11	0.11	0.11	0.11	0.11
CHANDLER, AZ	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.21	0.21	0.00	0.00	0.00
LEACH, NV	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.26	0.26	0.26	0.26	0.26
BRUNEAU-CRANDVIEW, ID	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.26	0.26	0.26	0.26	0.26
LASSEN, CA	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00
ALVORD, OR	0.00	0.00	0.00	0.29	0.00	0.00	0.00	0.29	0.29	0.29	0.29	0.29
SAFFORD, AZ	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WEISER/CRAVE CREEK, ID	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.11	0.11	0.11	0.11	0.11
VALE, OR	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.07	0.07	0.07	0.07	0.07
THERMO, UT	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.15	0.15	0.15
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.11	0.00	0.00	0.00	0.00
CLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.28	0.28	0.28	0.28
MOUNT BOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00
TOTALS	0.02	0.25	0.32	1.47	0.88	0.69	2.18	2.56	2.46	2.40	2.40	2.40

Table B-III. Savings Due to Improved Drilling Success for Production Wells
(10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
CEYSERS (STEAM), CA	0.15	0.50	0.44	0.80	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SALTON SEA, CA	0.00	0.00	0.02	0.00	0.07	0.07	0.08	0.12	0.12	0.12	0.12	0.12
VALLES CALDERA, NM	0.00	0.00	0.15	0.00	0.00	0.59	0.00	0.79	0.00	0.79	0.79	0.79
BRADY, NV	0.00	0.00	0.13	0.00	0.00	0.27	0.00	0.71	0.00	0.71	0.71	0.71
BRAWLEY, CA	0.00	0.00	0.03	0.00	0.05	0.00	0.15	0.17	0.17	0.17	0.17	0.17
ROOSEVELT, UT	0.00	0.00	0.05	0.00	0.00	0.10	0.00	0.14	0.00	0.27	0.27	0.27
BEOWAWE, NV	0.00	0.00	0.15	0.00	0.00	0.29	0.00	0.39	0.00	0.79	0.79	0.79
COSO, CA	0.00	0.00	0.00	0.00	0.20	0.23	0.27	0.94	0.94	0.94	0.00	0.00
MONO-LONG VALLEY, CA	0.00	0.00	0.00	0.00	0.20	0.00	0.55	0.00	0.00	0.62	0.00	0.00
COVE FORT/SULFURDALE, UT	0.00	0.00	0.00	0.00	0.45	0.00	0.63	0.00	0.72	0.72	1.44	1.44
NEBER, CA	0.00	0.00	0.00	0.00	0.22	0.00	0.30	0.00	0.70	0.70	0.70	0.70
CEYSERS (HYDRO), CA	0.00	0.00	0.00	0.00	0.78	0.93	1.09	1.24	1.24	1.24	1.24	1.24
EAST MESA, CA	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.41	0.00	0.00	0.00	0.00
STEAMBOAT, NV	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.19	0.00	0.38	0.00	0.00
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.70	1.41	1.41	1.41	1.41
CHANDLER, AZ	0.00	0.00	0.00	0.00	0.00	0.93	0.00	0.00	0.00	2.48	1.24	0.00
LEACH, NV	0.00	0.00	0.00	0.00	0.00	0.00	1.63	0.00	0.00	1.86	3.73	3.73
BRUNEAU-GRANDVIEW, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.00	0.00	2.02	2.02	2.02
LASSEN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.25	0.00	0.00
ALVORD, OR	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.00	0.00	1.15	1.15	1.15
SAFFORD, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00
WEISER/CRAZE CREEK, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.00	2.01	2.01	2.01
VALE, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.64	0.64	0.64
THERMO, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.00	1.15
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.82	0.00	1.82	0.00	0.00
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.00	0.00
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.32	2.65	2.65
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.34	0.00	0.00
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.10	0.00	0.00
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.66	0.00	0.00
TOTALS	0.15	0.50	0.97	0.80	2.84	3.95	7.69	9.85	5.29	28.38	21.07	20.98

Table B-IV. Savings Due to Improved Drilling Success for Replacement Wells
(10⁶ 1979 Dollars)

SITE	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
GEYSERS (STEAM), CA	0.04	0.10	0.17	0.27	0.38	0.51	0.64	0.73	0.73	0.73	0.73	0.73
SALTON SEA, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.03	0.06	0.07
VALLES CALDERA, NM	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.12	0.12	0.20	0.20	0.28
BRADY, NV	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.07	0.07	0.14	0.14	0.21
BRAWLEY, CA	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.07	0.09
ROOSEVELT, UT	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.03	0.03	0.04	0.04	0.07
BEOWAVE, NV	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.00	0.03	0.12	0.12	0.20
COSO, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.09	0.19	0.28	0.37
MONO-LONG VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.09	0.09	0.09	0.16
COVE FORT/SULFURDALE, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.07	0.14	0.14	0.22	0.29
HEBER, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.07	0.07	0.14	0.21
GEYSERS (HYDRO), CA	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.25	0.37	0.50	0.62	0.75
EAST MESA, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.08	0.08	0.08
STEAMBOAT, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.04	0.04	0.08
SURPRISE VALLEY, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.07	0.14	0.28	0.42
CHANDLER, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.12	0.12	0.12	0.37
LEACH, NV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.19	0.19	0.37
BRUNEAU-GRANDVIEW, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10	0.30
LASSEN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.05
ALVORD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.12	0.12	0.23
SAFFORD, AZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10	0.10
WEISER/CRAVE CREEK, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.30
VALE, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.13
THERMO, UT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.06
RAFT RIVER, ID	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.18	0.36
GLASS MOUNTAIN, CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09
PUNA, HI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
MOUNT HOOD, OR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.13
BAKER HOT SPRINGS, WA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21
W. YELLOWSTONE, MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17
TOTALS	0.04	0.10	0.17	0.27	0.47	0.62	1.09	1.77	2.63	3.63	4.16	7.00

more than one developer, and thus that subsequent accelerations may occur. A maximum acceleration of three months was assumed and a five year schedule for realization of this maximum was assumed as explained in Section 3.4. Benefit was calculated based on the equivalent amount of oil that would have been required to generate the extra electricity made available by the acceleration of power-on-line.

All these benefits are necessarily calculated from average estimates for a wide variety of sites and wells. Actually of course, the benefits will not be realized in this way, but rather as minor benefits in many areas and major savings for a few resources and some isolated wells.

APPENDIX C

Since the log interpretation program is intended to aid development of geothermal resources by providing analytical tools needed by developers and since the benefits of improved log interpretation can only be realized if the techniques are used, industry input played an important part in the cost/benefit study. In addition to the input of SAI's consultants, interviews were sought with personnel involved with the use of well log data in geothermal development for two purposes, the first was obtaining industry input on the direction research should take and on industry's use of logging and its most urgent needs, and the second was for validation of the benefit estimates made. The following is a list of trips made under the contract.

<u>Contact with</u>	<u>Date</u>
San Diego Conference on Cerro Prieto, Mexico	20-21 Sept 78
Los Alamos Scientific Laboratory Los Alamos, N.M.	11 Oct 78
Sandia Laboratories Albuquerque, N.M.	25 Oct 78
Union Oil, Los Angeles, CA	30 Nov 78
Republic Geothermal, Santa Fe Springs, CA	7 Dec 78
LASL GLIP Steering Committee Meeting, Monterey, CA	10-12 Dec 78
Phillips Petroleum, Salt Lake City, UT	15 Dec 78
Chevron Resources, San Francisco, CA	21 Feb 79
George Zebal, consultant for Magma Power Company, Newport Beach, CA	19 & 25 Jan 79

APPENDIX D
Discount Rates and Present Value

One of the most complex features of any cost/benefit analysis of this sort lies in the fact that fundamental to the entire process is the comparison of values across substantial separations in time. How is a cost of dollars, expended today, to be compared to the eventual yield of that investment which will be achieved many years in the future? A dollar received today is worth more than a dollar received a year from now. The standard solution is to apply a "discount rate" to sums of money that are to be expended or received in the future in order to calculate the "present value" of those amounts. At several points in this report discount rates are applied to the costs and benefits being estimated, and it seems appropriate to give some indication here of exactly what was done.

The first item that must be mentioned is inflation. In this report all values have been calculated in terms of costs and prices for 1979. That is, the costs and benefits are expressed in terms of the purchasing power of the dollar in 1979 (for example, the cost of a well at a given site is assumed to be the same regardless of when it is drilled). Thus the effect of inflation has been removed. However, this alone is not sufficient to allow us to compare a quantity V, of dollars in the present with another quantity W of dollars some number, N, years in the future. A private citizen or corporation could invest the sum V in the present at an annual return on investment R. N years from now the value of this investment will be $V(1 + R)^N$. Then when

V = Dollar invested in the Present

W = Dollars returned in the Future

R = Return on Investment

N = Number of years in the Future

$$W = V (1+R)^N$$

The present value of a future revenue can be computed by the formula

$$V = \frac{W}{(1+R)^N}$$

Looking into the future each year's expenditures and revenues must be discounted to reflect the value of money over time.

The question that remains is the selection of an appropriate discount rate for use in calculating the present value of future federal expenditures and of future benefits from federal programs. The American people acting as a whole through their government do not necessarily seek the same rate of return as does a private individual or industry because the government may seek very much longer term goals than would an individual.

It could be argued that a zero discount rate is appropriate. Another discount rate that is sometimes used is the prime rate, the rate of return the government receives for money lent to banks through the Federal Reserve System. In applying a discount rate, it must be kept in mind that in this study the effect of inflation is already removed. Where

I = Inflation rate

R = Discount Rate or inflated dollars

V = Dollars invested in present

W = Dollars returned in the Future

N = Number of years in the Future

$$W = \frac{V(1+R)^N}{(1+I)^N}$$

in year 1 the effective discount multiplier would be

$$\frac{(1+R)}{(1+I)}$$

the discount rate would be

$$\frac{(1+R)}{(1+I)} - 1$$

Thus, if at present the prime rate is in the vicinity of 10% with 8% inflation, this means that the appropriate discount rate on constant dollars would be $\frac{(1.10)}{(1.08)} - 1 = 1.85\%$ (note that the correct discount rate is not exactly the simple difference between return on investment and inflation). A discount rate appropriate for private industry could be used. Many industries are now seeking a return on investment of 15 to 20%. Again considering 8% inflation, this means a discount rate on constant dollars of 6.5 to 11.1%.

In this study, the selection of a single discount rate has been avoided, instead results for discount rates of 0, 5, and 10% are presented. Based on the calculations presented above it would appear that an appropriate discount rate would be 2 to 5%.

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