PROGRAMMATIC OBJECTIVES
OF THE
GEOTHERMAL TECHNOLOGY DIVISION

VOLUME I

PART A: RESEARCH OBJECTIVES
IN A COST-OF-POWER CONTEXT

PART B: IMPLEMENTATION OF OBJECTIVES
IN THE RESEARCH PROGRAM CONTEXT

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U.S. DEPARTMENT OF ENERGY
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PROGRAMMATIC OBJECTIVES
OF THE
GEOTHERMAL TECHNOLOGY DIVISION

PART A: RESEARCH OBJECTIVES
IN A COST-OF-POWER CONTEXT
PREFACE

Goals comprise the yardstick by which the success of any endeavor is measured. They are devised to motivate those involved in achieving them into profitable courses of action.

Good goals share three common attributes. First, they are understandable to the target group to which they apply. The goal statements are simple, straightforward, and unequivocal; generally they satisfy a well-perceived need or offer a benefit to the target group.

Secondly, the goals are attainable in a practical sense. In the context of planning a research and development program, this means that within a given time frame, adequate capability and resources exist. Impractical goals, no matter how worthwhile, will not produce the desired result.

The last attribute is somewhat the product of the first two, but no less important: good goals are acceptable as indicators of the direction in which the target group wishes to move. Depending on the issues and related goals involved, acceptability can be judged on technical, business, social, and/or even ethical grounds. Given those judgments, the target group appreciates and accepts the overall benefit derived from achieving the goal.

When the above attributes are present in a goal-oriented endeavor, they infuse a commitment to the goal, thereby greatly increasing the likelihood of success.

This document contains the multipurpose objectives of the geothermal energy research program sponsored by the Department of Energy. Those objectives will govern the direction of our future research. We believe they satisfy the three attributes of good goals. However, that belief can only be sustained by the endorsement of the target group, which in this case includes the geothermal industry. This document is intended as a vehicle for obtaining that endorsement.
SUMMARY

The Geothermal Technology Division (GTD) of the Department of Energy uses management by objectives to direct its research program. This draft statement contains the entire set of GTD's geothermal research objectives and the reasoning behind them. Through this document we seek to inform persons with an interest in geothermal energy about our research objectives for the next five years. In addition, we solicit comment from those persons on the appropriateness and relevance of those objectives. We consider this feedback essential to the success of our research program.

We recognize three levels of objectives which govern the content of GTD's program. Level I objectives provide a target for decreasing the total cost of power for generating electricity from geothermal energy. Level II objectives address incremental improvements in the cost and/or performance of major system components that make up a geothermal power project. And Level III objectives identify improvements in cost, efficiency, and certainty of performance to which our individual research activities are geared. A Geothermal Energy Project Cost Tree shows how the three levels relate to one another.

The achievement of research objectives (Level III) ultimately influences the total cost of power (Level I). The magnitude of this effect is estimated with a cost-of-power model which translates improvements in technology brought about by research into reductions in the cost of power. The model is based on actual operating experience from geothermal power plants and uses reference data from eight site-plant configurations; it is described at length in Appendices A and B.

For the present, the cost-of-power model applies solely to the use of hydrothermal resources. Models for other resource types (i.e., geopressed, hot dry rock, and magma) have not yet evolved. However, the project cost tree offers a simple, consistent means of expressing research objectives for these resources. At present, the Level I objectives for each resource type are:

- **Hydrothermal** - Reduce the life-cycle cost of producing electricity from liquid-dominated, moderate- to high-temperature hydrothermal resources to 3 to 7 cents per kilowatt-hour (kWh) by 1992. This compares with a cost range of 4 to 15 cents/kWh for hydrothermal electric energy as of 1986.

- **Geopressed-Geothermal** - Improve the technology to the point where energy could be produced commercially from the geopressed resource at a cost equivalent to 6 to 10 cents/kWh by 1995.

- **Hot Dry Rock** - Provide the technology to enable industrial hot dry rock projects to generate power at 5 to 8 cents/kWh by 1997.

- **Magma** - Create the technology by which energy could be produced experimentally from magma energy at an equivalent cost of 10 to 20 cents/kWh by the year 2000.

The cost-of-power numbers are normalized to the base year of 1986. For the hydrothermal case, the range in the numbers is due to cost differences among the various site-plant combinations in the model. The ranges for the other resources represent the product of different economic analyses and prognoses by experts on likely changes in technology. The year specified for achieving the objective reflects the target for
completing all subordinate research objectives (Level III) and not necessarily the year in which cost savings will be realized by industry. Reductions in the cost of power should accrue incrementally as industry adopts the new technology and gains operating experience.

The text summarizes the research being undertaken to achieve the Level III objectives. More complete descriptions can be found in other GTD program documents such as the multiyear program plan or annual operating plans.

Our research objectives are not fixed; we expect they will change in response to available funding or as additional knowledge and experience are gained. Some lines of research may have to be abandoned if they prove unsuccessful. Others may take their place if they have potential for ultimately reducing the cost of power. The geothermal industry possesses the knowledge and experience needed to help us make decisions about the research program. By working together cooperatively in exchanging ideas and information, GTD and the industry can make geothermal energy a viable economic option for the Nation.
1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to define the objectives of the geothermal research program of the Geothermal Technology Division (GTD). A corollary purpose is to elicit comment from the public on whether the stated objectives satisfy the three attributes of good objectives: are they understandable, attainable, and acceptable?

The intended audience includes anyone with an interest in finding, producing, and using geothermal energy in its various forms. In particular, this includes those persons involved with the development and application of geothermal technology (i.e., researchers, suppliers, manufacturers, producers, users, and financiers). GTD's research program is intended to serve that group. And the group's participation in verifying the program's objectives is vital to the success of the program.

This document has value to the GTD as a unified, comprehensive source of objectives statements. But of greater importance than a compilation of objectives, the document explains how those objectives are derived and used to guide our research. (Note: For ease of discussion, goals and objectives are considered synonymous, and the term "objectives" is used herein for both.)

1.2 ROLE OF OBJECTIVES IN THE GEOTHERMAL PROGRAM

The objectives of GTD's research program are derived from a series of interactions, conceptualized in Figure 1-1. The nodes in the diagram represent activities, decisions, and information sources. The connecting lines depict the flow of information between nodes.

The choice of appropriate program objectives is driven by two unique factors: industry's need for improved technology (node 1); and government policies that determine which research areas are suitable for Federal support (node 2). The two factors can exert conflicting pressures on the program: the former is the product of near-term market opportunities and economic considerations, while the latter must also deal with the Nation's long-term energy security. The resultant set of objectives (node 3) reflects the influence of both factors.

Once established, the objectives define a collection or portfolio of plausible research options which the program can implement (node 4). From the available options GTD selects those which comprise its research and development program. That selection is based on criteria such as feasibility, cost, schedule, and likelihood of achieving positive results. The program functions via research activities executed by industry, universities, and national laboratories (node 5). The results are passed along to industry through a variety of technology transfer mechanisms (node 6).

The real utility of improved technology can only be gauged from practical application by industry (node 7). Operating experience enables industry to identify further technology improvements (node 1), and it also gives GTD essential information to analyze performance (node 8). Analysis of performance then becomes the means for judging success in achieving the objectives.
FIGURE 1-1
Origin and Roles of GTD Goals and Objectives

INDUSTRY ACTIVITIES

1 Industry Needs for Technology
2 Government High-Level Policies
3 R&D Program Goals and Objectives
4 Portfolio of R&D Options
8 Analysis of Technology Performance
5 Execution of R&D Projects
6 Technology Transfer
7 Industry Use of Technology
GTD uses information provided by industry as a feedback mechanism to modify the R&D program (node 3). If need be, objectives are adjusted to reflect actual operating experience. Or practical experience may dictate changes in the choice of research options (node 4) or the manner in which the options are executed (node 5).

Analysis of performance (node 8) occupies a pivotal point in the research planning process. And the means used for analyzing performance, at least for hydrothermal systems, is the IM-GEO cost-of-power model, described in section 2.2. At present, this model offers the only mechanism by which the cost impacts of incremental improvements in technology can be gauged quantitatively. The model derives from actual industry experience, and its validity depends on a regular flow of information from industry about the performance of new technology.

Whereas the model serves as a useful analytic tool, it does not constitute the last word in judging performance. Judgments of performance and, consequently, achievements of objectives require the consultation and cooperation of GTD and its contractors and industry partners. Hence we show the tie line between industry use and performance analysis in Figure 1-1.

The process depicted in Figure 1-1 has functioned for a number of years on a largely informal basis. Through various avenues, such as the Geothermal Drilling Organization and the Geothermal Technology Organization, industry has identified research needs. GTD and industry have often collaborated on topics of mutual interest, especially in the area of reservoir technology research. Industry has generously shared information on geothermal components such as exploration and production wells, logging instruments, pumps, and turbines. GTD has used that information to help in structuring its program. This document should enable interested persons to understand better how the process works and to appreciate industry's role in that process.
2.0 CONCEPTUAL BASIS FOR DEFINING RESEARCH PROGRAM OBJECTIVES

The general precept underlying the research objectives is that the cost of energy can be reduced through achievements in research. Those achievements may come about through a variety of means including improvements in system performance (e.g., better condenser efficiency), reduction in uncertainties of system performance (e.g., reliable predictions of reservoir productivity), or development of new systems (e.g., radar fracture mapping tool). While such achievements represent only discrete advances in technology, their link to reductions in cost remains to be defined.

There are thus two main tasks in formulating the conceptual basis of our research objectives:

- Specifying the relationship of research objectives (i.e., achievements) to real-world energy projects, and
- Quantifying the effects of those objectives upon the cost and performance of energy projects.

The first of these tasks is accomplished in Section 2.1, which describes a hierarchy for objectives and relates those objectives to power system cost components.

The second task is covered in Section 2.2, which describes a cost-of-power model that was developed and used to analyze quantitative impacts of technological achievements.

Section 2.3 clarifies the relationship of the research objectives to the current priorities and resources of the Geothermal Technology Division research program. Section 2.4 describes how recently achieved improvements in technology are factored into the analysis.

2.1 OBJECTIVES HIERARCHY

A typical geothermal energy project has several well-defined cost components. In order to facilitate analysis of technology improvements, the research objectives are structured in a hierarchy that reflects those components. Four major cost components are recognized: (1) Resource Analysis - the effort to find and define a geothermal energy resource; (2) Fluid Production - the task to produce geothermal fluid and maintain that production; (3) Energy Conversion - the process of extracting useful energy (and byproducts) from the geothermal fluid and ultimately disposing of the fluid; (4) Other Operations - any cost factors which lie outside the first three components. There are other ways to organize the objectives; the above approach was chosen because it corresponds closely to industry practice and the structure of the cost-of-power model.

Each of the four components is made up of several cost elements, and those elements contain numerous cost factors, which themselves can be subdivided. Ultimately, every single cost of equipment, material, and service can be itemized in a multi-tiered, project cost "tree." For purposes of this discussion we need only consider the top three tiers or levels of the tree. These are shown in Figure 2-1. Note that the Geothermal Energy Project Cost Tree is generic. It applies to any resource type (i.e., hydrothermal, geopressed, hot dry rock, or magma), conversion scheme (i.e., flash or binary), and final use (i.e., electricity or direct heat).
FIGURE 2-1
Geothermal Energy Project Cost Tree

GEOTHERMAL ENERGY PROJECT

RESOURCES ANALYSIS
- Exploration
- Resource Definition
- Reservoir Evaluation
- Wellfield Design
- Reservoir Monitoring

FLUID PRODUCTION
- Drilling & Completion
- Stimulation
- Injection
- Well Maintenance
- Brine Treatment
- Pumps & Fluid Transport

ENERGY CONVERSION
- Heat Exchange Cycle
- Turbine - Generator
- Heat Rejection Cycle
- Fluid Control & Disposal
- Non-thermal Products

OTHER OPERATIONS
- Leasing
- Permitting
- Transmission
- General Environment & Safety
- System Optimization
- Finance
An explanation of the terms used in the cost tree is given in Table 2-1 (at the end of this section). Each term is defined briefly from the perspective of a geothermal developer. In some cases that perspective differs from that of a government official. This difference results from government's necessarily limited roles in research, regulation, and finance. The specific linkage between the cost tree and the government's research program is presented in subsequent sections of this document.

The three tiers of the cost tree provide the basis for defining three levels of research program objectives. These levels are illustrated in Figure 2-2 along with their expected impacts. Level I objectives represent the cumulative impact of the program on the total cost of power. Level II objectives specify the impacts on major components of the cost tree. And Level III objectives define the technological achievements expected from each element of the research program. Level III objectives are most pertinent to this discussion; the size of the impacts at Levels I and II derives from the Level III objectives through use of the cost-of-power model.

Level I objectives allow analysts and decision-makers to estimate the future cost of power from geothermal energy. At this level, the objectives are expressed in terms of reducing the life-cycle cost of energy from a typical geothermal energy production project.

Level II objectives give government and industry managers an impression of how much improvement is likely to occur within major project components as a result of Federally-funded research.

The Level III objectives prescribe the technical direction of individual research activities. They facilitate communication among engineers and scientists; they comprise the technical yardsticks by which progress can be measured.

At Levels II and III the usual impact of achieving an objective is that performance improves and that costs decrease. However, we note that other impacts are possible, including increases in the cost of a component in order to deliver a performance advantage that would reduce costs elsewhere in the system. For example, binary-cycle power plants with improved thermal efficiency could cost more than current binary plants, but they yield larger cost savings by reducing the amount of geothermal fluid required to produce a unit of energy.

For simplicity, the three levels of objectives are presented separately for each resource type: hydrothermal, geopressured, hot dry rock, and magma. As indicated previously, the cost tree (Figure 2-1) provides an organization for the research objectives in terms of project costs. However, not every element of the tree has an objective. For example, many elements (e.g., Leasing, Permitting) are not included in GTD's research program. Therefore, those elements have no objectives. On the other hand, a single element may have more than one objective.

The numerical code included with each Level III objective serves to link that objective to the research program described in Part B of this document.
Level I. IMPACTS ON COST OF POWER

Level II. IMPACTS ON PERFORMANCE OF MAJOR COMPONENTS
- RESOURCE ANALYSIS
- FLUID PRODUCTION
- ENERGY CONVERSION
- OTHER OPERATIONS

Level III. TECHNICAL OBJECTIVES OF R&D PROGRAM ELEMENTS
IMPACTS:
- Component(s) affected
- Technology performance improvements
- Technology cost reductions
- Completion schedule
Table 2-1. Description of Terms in Project Cost Tree

1. RESOURCE ANALYSIS

1.1 Exploration:

The application of geology, geochemistry, geophysics, and hydrology to the discovery of geothermal resources.

1.2 Resource Definition:

The application of earth science and engineering activities to determine the lateral and vertical boundaries of the geothermal system, the distribution of chemical and thermodynamic characteristics of different fluid types, the geological controls on permeability and fluid production, the production characteristics of the resource, the areas of upflow and recharge, and other similar characteristics of the resource.

1.3 Reservoir Evaluation:

Predictions of reservoir production characteristics, productive lifetime, and energy capacity.

1.4 Wellfield Design:

The design of production and injection well fields, including the choice of well locations, well plans, well completion designs, and fluid-flow rates. Designs optimize the economics of exploitation and the efficiency of energy production from the resource.

1.5 Reservoir Monitoring:

The application of earth science and engineering techniques to detecting and quantifying changes in the reservoir and the produced fluids during the production period.

2. FLUID PRODUCTION

2.1 Drilling and Completion

Activities associated with drilling and completing the wells used to find, develop, and produce geothermal energy.
Table 2-1. Description of Terms in Project Cost Tree (Continued)

2.2 **Stimulation**

The application of methods to enhance the productivity of geothermal wells.

2.3 **Injection**

The disposal of geothermal brines in the producing formation in order to help offset fluid production losses, maintain reservoir pressures, and reduce surface disposal.

2.4 **Well Maintenance**

The procedures used to assure that geothermal wells operate efficiently throughout their design lifetimes.

2.5 **Brine Treatment**

The use of substances or procedures on produced geothermal brine to (1) minimize harm to equipment or components from thermochemical attack; and (2) enhance the ease and efficiency with which the brine is used.

2.6 **Pumps and Fluid Transport**

The equipment and piping systems used to move geothermal fluids from the reservoir to the point of final disposal.

3. **ENERGY CONVERSION**

3.1 **Heat Exchange Cycle**

The means to transfer heat from geothermal fluid to a working fluid for conversion to mechanical power.

3.2 **Turbine - Generator**

Equipment used to convert thermomechanical power into electric power.

3.3 **Heat Rejection Cycle**

The process of transferring waste heat from a power cycle to the ambient environment.
Table 2-1. Description of Terms in Project Cost Tree (Continued)

3.4 **Fluid Control and Disposal**

Equipment, materials, and procedures used to manage the flow of fluids within a geothermal facility, detoxify those fluids, provide suitable packaging for wastes, and enable the ultimate disposal of wastes.

3.5 **Non-thermal Products**

Products of geothermal energy production other than heat and electricity.

4. **OTHER OPERATIONS**

4.1 **Leasing**

The process of acquiring rights of access to geothermal resources for purposes of exploration, production, and utilization.

4.2 **Permitting**

The legal means of enabling the production and sale of geothermal energy.

4.3 **Transmission**

The rights-of-way, access, and equipment needed to carry energy produced from geothermal resources to consumers.

4.4 **General Environment and Safety**

Designs, equipment, and procedures needed to assure compliance with laws, rules, and regulations governing the protection of the environment, workers, and the public from hazards associated with the production of geothermal energy.

4.5 **System Optimization**

The engineering and economic analyses related to design, construction, and operation to maximize the return on investment in a geothermal facility.

4.6 **Finance**

The process of acquiring funds to find, produce, convert, and sell geothermal energy.
2.2 COST-OF-POWER MODEL

As indicated previously, analysis of performance is a critical step in determining geothermal objectives and the content of GTD's program. Until recently, the analysis was largely qualitative, necessitating considerable subjective judgment on the part of GTD's managers. That subjectivity has been reduced by the introduction of a quantitative, cost-of-power model (IM-GEO, "Impacts of Geothermal Research", developed by Sandia National Laboratories, March 1987). The model simulates interactions among the major cost components of a hydrothermal electric power plant. Accordingly, the cost savings of technology improvements resulting from GTD's hydrothermal research program can be estimated. Industrial experience forms the basis for many of the model's algorithms. A description of the model is given in Appendix A.

The cost-of-power model enables an analysis of impacts from each element of the hydrothermal research program. For instance, the impact on the cost of power from a 20 percent decrease in well drilling costs can be estimated. Usually the impacts are multiplicatively interdependent. For example, improvements in brine treatment technology and well maintenance procedures that might separately each produce a 2 percent reduction in the cost of power, when combined might result in less than a 4 percent decrease in the total cost of power. Sensitivity analyses can be done to help find which technology improvements will have the greatest overall impact, either singly or in combination.

Given its flexibility and its use of actual operating experience, the model is useful for developing objectives as well as for verifying their impact on cost of power. The upper level hydrothermal objectives (Level I and Level II) are derived applying the IM-GEO model to the Level III objectives. The Level I and Level II objectives are, therefore, higher-order economic consequences that will result if all of the Level III objectives are met.

The IM-GEO model estimates baseline costs of power (and changes due to technology improvements) for each of eight modeled regions via single-point estimates of performance and cost for major project components. Ranges are assigned to the point estimates using rules of thumb. IM-GEO integrates more than 40 physical characteristics for the eight regions, about 60 technology-improvement terms, and more than 400 primary terms or relationships that define the performance and cost of hydrothermal electric projects. Appendix B describes the application of the model.

GTD initially considered using explicit Monte Carlo calculations for these estimates, but saw little to be gained by using a more complex approach. However, the impacts that uncertainties in reservoir characteristics have upon the financial risk in each region are calculated in a way that takes into account the probabilistic nature of the reservoir uncertainties.

The model has evolved through time, and future improvements in its algorithms are likely, especially as industrial experience accumulates. These improvements could suggest changes to the objectives. None of the objectives presented here should be considered as fixed or absolute, but rather as targets indicative of the current state of knowledge. Furthermore, the modeling effort is, in itself, research. This research sometimes requires the use of simplifying assumptions and occasional guesses to quantify variables that are known to be critical to system performance but have not yet been well-measured.

While the cost-of-power model makes a credible simulation of hydrothermal electric projects, its current applicability to other resource types is limited. Models for the other
resource types (geopressed-geothermal, hot dry rock, and magma) are currently under development. Once those models achieve an adequate degree of reliability, they will be used to formulate quantitative higher-level objectives.

2.3 RELATIONSHIP OF OBJECTIVES TO PROGRAM PRIORITIES AND FUNDING

The statements of research objectives herein are not intended to reflect any relative priority ranking. The priorities of the Federal Geothermal Program change in response to policy directives, industry needs, new concepts for technology improvement, and the overall Federal budget for energy technology research. Relative priorities among the various geothermal technical areas are reflected in the Administration's budget proposals and congressional appropriations.

The attainment of objectives is, of course, dependent on the availability of resources, especially funds. GTD believes that the objectives in this document represent an attainable set of technology improvements, given the funding situation at the time the objectives were formulated (i.e., circa 1987-88). Research work is continuing on each objective, and progress is being made. Precise knowledge of funding needed to maintain that progress does not exist, given the risks and uncertainties of research.

GTD has purposely avoided an estimation of future budget levels because we do not want this issue to predominate the research objectives. The objectives are intended to answer the question, "Where are we going?" In part, budgets deal with the questions, "How do we get there and when?" GTD recognizes that these questions are interdependent. The objectives expressed herein are not fixed; they are subject to change. And one of the variables of change is available funding.

2.4 RECENT TECHNOLOGY IMPROVEMENTS

The assumptions about hydrothermal technology performance and cost in the IM-GEO model result from technology that was being used by U.S. industry at the beginning of 1986. Those assumptions form a baseline for the cost of power against which the economic impacts of technology improvements can be gauged. Improvements in hardware and other aspects of technology have occurred since early 1986. These technology improvements are analyzed to account for their impacts on hydrothermal system economics.

Recent hydrothermal technology improvements of which GTD is aware are described in section 3.5. Their estimated impacts on the cost of power are addressed during discussion of the hydrothermal Level I objective in section 3.0.
3.0 HYDROTHERMAL RESEARCH OBJECTIVES

The GTD research program for hydrothermal energy deals with liquid-dominated, moderate-temperature resources, which comprise the bulk of known hydrothermal resources. In particular, the program concentrates on improving technology associated with generating electricity from geothermal energy.

At present, there are no objectives aimed specifically at direct-heat applications (e.g., aquaculture, space heating). Geothermal technology for low-temperature, direct-heat uses appears not to require a special research effort. Many of the research tasks for hydrothermal electric systems, such as reservoir engineering and drilling, have application to direct-heat use. However, GTD will continue to monitor direct-heat developments for needed technology improvements.

The Level I objective for hydrothermal research is to reduce the life-cycle cost of producing electricity from liquid-dominated, hydrothermal resources to 3 to 7 per kilowatt-hour (kWh) cents by 1992.a This compares with a cost range of 4-15 cents/kWh for hydrothermal electric power as of 1986. The equivalent weighted average reduction in cost of power is 30 to 40 percent.

The following notes elaborate on the basis for the objective:

- The magnitude of the estimated cost improvement is based on changes in the weighted average of the cost of power for the eight modeled cases: four flash plants and four binary plants operating under varying reservoir conditions. The resource conditions that were modeled are reflective of the bulk of U.S. commercial hydrothermal resources, which include high-temperature as well as moderate-temperature reservoirs.

- The weights used in the averages are derived from estimates of U.S. hydrothermal resources that could be developed using the improved technology assumed in each of the eight cases. This provides reasonable assurance that the cost improvements could be attained for U.S. hydrothermal energy projects constructed in the post-1992 period if GTD's research objectives are met.

- A portion of the cost improvements in the Level I objective comes from technology improvements that have already been attained since the beginning of 1986, the baseline date for this analysis. About 9 percent of the overall cost-reduction in the objective is estimated to be due to those improvements. This reduction is equivalent to about 0.2 to 0.4 cents/kWh. The technology improvements are identified in Section 3.5.

(a) Any milestone date included in an objective is the expected date for completion of the stated technology improvement by GTD. The actual cost benefits will accrue in subsequent years as industry adopts the technology and gains practical operating experience. The significance of the cost ranges shown here and elsewhere is discussed in Section 4.1 of Appendix B.
GTD is aware that some hydrothermal reservoirs are already producing power at costs of 3.5 to about 8.0 cents per kWh, levelized in constant dollars. However, substantial amounts of identified hydrothermal resource, as analyzed by the IM-GEO model, today lie in an estimated cost band of 8.0 to about 15.0 cents/kWh. In addition, some of the power that is being developed today at 6.5 to 8.0 cents/kWh could be non-economic if developed without the availability of current tax incentives (e.g., the Federal renewable energy tax credit) or if State-specific PURPA contract prices decline, as they have since the recent decline in avoided costs.

The technology improvements sought via GTD's Level III research objectives are especially important for hydrothermal prospects where the physical conditions are currently marginal from an economic point of view. Those improvements should affect a number of locations where no geothermal electricity is being produced today, as well as enhance the competitiveness of some producing reservoirs.

The Level I objective is to be achieved through the implementation of a comprehensive research program designed to produce technology improvements over many cost elements. Figure 3-1 shows the cost tree for hydrothermal electric projects. The solid dots indicate those elements affected by GTD's current research program.

The expected impacts on the life-cycle cost of power from GTD's current R&D Program, at the four major branches (Level II) of the hydrothermal cost tree are:

- Resource Analysis - 15 to 22 percent reduction
- Fluid Production - 6 to 9 percent reduction
- Energy Conversion - 9 to 14 percent reduction overall
- Other Operations - No direct impact expected.

The sum of the impacts expected at Level II is somewhat greater than the size of impact estimated for the Level I objective. This apparent discount in the overall impact occurs because the Level II impacts along each branch of the tree are calculated independent of contributing effects of R&D along the other branches. As indicated earlier (Section 2.2), when improvements are considered together, complex interactions diminish some of the cost savings. This effect is described further in Section 4.0 of Appendix B.

3.1 HYDROTHERMAL RESOURCE ANALYSIS

The Level II Objective for Hydrothermal Resource Analysis is:

*Reduce the life-cycle cost of hydrothermal electricity by 15 to 22 percent through improvements in exploration and reservoir confirmation technology and procedures by 1992.*
FIGURE 3-1
Focus of GTD Hydrothermal R&D Elements upon Electric Project Subsystems

HYDROTHERMAL ELECTRIC PROJECT

RESOURCE ANALYSIS
- Exploration
- Resource Definition
- Reservoir Evaluation
- Wellfield Design
- Reservoir Monitoring

FLUID PRODUCTION
- Drilling & Completion
- Stimulation
- Injection
- Well Maintenance
- Brine Treatment
- Pumps & Fluid Transport

ENERGY CONVERSION
- Heat Exchange Cycle
- Turbine - Generator
- Heat Rejection Cycle
- Fluid Control & Disposal
- Non-thermal Products

OTHER OPERATIONS
- Leasing
- Permitting
- Transmission
- General Environment & Safety
- System Optimization
- Finance

- Cost Items Affected by GTD Hydrothermal Program Elements
This cost improvement is exclusive of improvements expected from research associated with the other branches of the hydrothermal cost tree. The improvement consists of:

- A 17 to 26 percent reduction in the cost of exploration activities, due mainly to an increase in the probability of success in siting exploration (wildcat) wells.

- A 36 to 55 percent reduction in the cost of reservoir confirmation activities, due mainly to a decrease in the drilling and testing activity needed to confirm a reservoir.

- A 21 to 31 percent reduction in life-cycle costs of the production field, due to decreases in uncertainty about the long-term performance of the reservoir and to improvements in well siting relative to production zones.

- An 8 to 11 percent reduction in life-cycle costs of the power plant, due to decreased uncertainty about the performance of the reservoir.

Note that the first three items do not include cost reductions from improved drilling technology, but only cost reductions from improved well siting and testing.

Because of insufficient historical information, progress toward this objective must be measured on the basis of expert opinion rather than detailed quantification. GTD is aware that special difficulties inhere with respect to quantifying geothermal reservoir performance and risks. However, we believe that enough information has accumulated in the past decade to place estimates upon a much more quantitative footing. Improved sensors, test procedures, and interpretations can reduce industry's uncertainties about short- and long-term reservoir characteristics, and those uncertainties should be expressible quantitatively.

The quantification in the IM-GEO model and in the estimates for the R&D objectives in the Resource Analysis area represents a first attempt to place GTD's reservoir technology research on a more rational basis. GTD welcomes any suggestions on how to improve concepts and quantification in this area, including better ways to quantify research progress in terms of measurable results.

The specific research objectives (Level III) on which the Level II objective is based are given as follows.

3.1.1 Exploration

**Issue:** Most of the obvious hydrothermal systems have been explored, and new discoveries will require exploration in frontier areas where the systems are concealed or at greater depths or adjacent to presently uneconomic systems. The success ratio for wildcat exploration holes is much lower for geothermal than it is for petroleum or mineral exploration. That ratio needs to be improved to help lower the cost of geothermal development.
**Level III Objectives:**

Increase the success ratio of wildcat exploration wells, especially in frontier areas such as the Cascades, by 20% by 1992. [H12-01]

Devise better methods and strategies for discovering hidden hydrothermal systems and for exploring the deep portions of known systems so that industry can locate three such hidden reservoirs by 1992. [H12-02]

3.1.2 **Resource Definition**

**Issue:** Resource definition involves defining the key parameters of a resource in the most efficient and economical way possible after the success of the first discovery well. Significant practical problems exist in establishing the vertical and lateral boundaries of the reservoir, the chemistry and enthalpy of fluids, the controls on permeability, and the areas of upflow and recharge. Preferably these problems must be solved using only a minimum number of wells.

**Level III Objectives:**

Reduce the number of wells needed to define the resource by 33% by 1992. [H11-01]

Decrease uncertainties in forecasting short-term and long-term changes in reservoir characteristics (i.e., fluid temperature, pressure, flow rate, and chemistry) by 10% by 1992, by increasing the accuracy and precision of information required for models of reservoir characteristics and performance. [H11-02]

3.1.3 **Reservoir Evaluation**

**Issue:** Large uncertainty exists in estimates of the energy capacity and productive lifetime of a geothermal reservoir. These estimates are needed to determine the economic feasibility of a project. This issue has a major impact on cost because it influences (a) the design and sizing of the power plant, and (b) project financing.

**Level III Objectives:**

Reduce uncertainties in predictions of reservoir capacity by 15% by 1992. [H11-03]

Decrease uncertainties in forecasting short-term and long-term changes in reservoir characteristics (i.e., fluid temperature, pressure, flow rate, and chemistry) by 15% by 1992 by improving reservoir evaluation methods. [H11-04]

Reduce the number of wells needed to evaluate a reservoir by 10% by 1992. [H11-05]
3.1.4 Wellfield Design

**Issue:** A successful geothermal field operation requires a continuous supply of brines of predictable thermodynamic properties and an adequate injection capacity. For these purposes, a wellfield design and management program has to be developed that optimizes the number and placement of wells needed to exploit the field. This includes considerations of well location, completion design, operation of production and injection wells, and plans for replacement wells that might be needed as field exploitation continues.

**Level III Objectives:**

Increase the success ratio of in-fill wells for production and injection (i.e., decrease the dry-hole ratio for in-fill wells) by 33% by 1992. [H13-01]

Improve methods for siting and designing geothermal production and injection wells in order to reduce the aggregate cost of wells by 15% by 1992. [H13-02]

3.1.5 Reservoir Monitoring

**Issue:** The complexities of hydrothermal systems presently preclude our being able to predict their performance in all details. Changes in enthalpy and chemistry of the produced fluids occur when the natural system is sufficiently perturbed by production. A carefully designed monitoring program is needed to detect reservoir problems at their earliest stages and to confirm the soundness of the production and injection method being used. Monitoring is necessary for understanding reservoir processes, for planning field expansion, and for mitigating environmental impacts.

**Level III Objectives:**

Decrease uncertainties in forecasting short-term and long-term changes in reservoir characteristics (i.e., fluid temperature, pressure, flow rate, and chemistry) by 10% by 1992, by improving reservoir monitoring methods. [H13-03]

Reduce the number of low-flow and short-lived production and injection wells drilled after production begins by 15% by 1992. [H13-04]

Improve the efficiency of the production and injection schemes to reduce the number of make-up wells by 10% by 1992. [H13-05]

Reduce uncertainties related to long-term reservoir changes in fluid temperature and injection break-through by 10% by 1992. [H13-06]

Reduce the number and severity of unexpected environmental problems, especially those related to induced seismicity and subsidence. [H13-07]
3.2 HYDROTHERMAL FLUID PRODUCTION

The Level II Objective for Hydrothermal Fluid Production is:

Reduce the life-cycle cost of hydrothermal electricity by 10 to 13 percent through improvements in fluid production technology by 1992.

This cost improvement is exclusive of improvements expected from research associated with the other branches of the hydrothermal cost tree. The improvement consists of:

- A 14 to 21 percent reduction in the cost of exploration.
- A 13 to 19 percent reduction in the cost of reservoir confirmation.
- A 13 to 19 percent reduction in the life-cycle cost of the well field.

All of these result mainly from expected reductions in the cost of drilling and completing individual wells.

The specific research objectives (Level III) on which the Level II objective is based are as follows.

3.2.1 Drilling & Completion

**Issues:** When considering the overall costs of a geothermal project, a significant fraction of the capital costs (35 to 50 percent) is for drilling of wells. This is due primarily to difficulties encountered during geothermal drilling as compared to oil and gas drilling. Equipment and materials used in geothermal wells must be capable of withstanding corrosive fluids and high temperatures for prolonged periods.

**Level III Objectives:**

Decrease the cost of drilling production-related geothermal wells by about 5 percent by 1992, through better identification of fractures. [H23-01]

Reduce the costs of deep wells and directionally drilled wells by 10 percent by 1992. [H22-01]

Decrease the uncertainties in measurements of downhole and wellhead temperature, pressure, and flow for moderate-temperature reservoirs by 25 percent by 1989. And decrease the uncertainties for similar measurements at reservoir temperatures greater than 250°C, by 50 percent by 1992. [H23-02]

Develop related drilling technology to effect an additional 5 percent reduction in well costs by 1990 and 10 percent by 1992. [H24-01]

Reduce costs associated with lost circulation episodes by 30 percent by 1992. [H21-01] and [H32-01]
Develop well-cementing materials with service lifetimes of 30 years at 400-600°C by 1991. [H32-02]

3.2.2 Stimulation

There are no R&D objectives for this cost area.

3.2.3 Injection

Issue: If production of fluid from a geothermal reservoir exceeds the natural recharge, the pressure in the reservoir will decline over time. This pressure decline will ultimately limit the productive lifetime of the reservoir. Injection of fluid, either cooled geothermal water or surface water, is critical to extending the productive life of a reservoir by extracting a greater portion of the thermal energy in the rocks. The injection of cool water has the risk of cooling the production wells and ending their useful life.

Three fronts move through the reservoir from the injection wells toward the production wells. The first is the desired pressure front that augments the pressure supplying the production. The second to arrive is a chemical front that reflects any chemical differences between the injected water and the reservoir fluid. The third front moving through the reservoir is temperature, and the arrival of this front kills production. Injection wells are sited to obtain the greatest advantage from the pressure effect and to delay the damaging results from the temperature effect.

There are no R&D objectives for this cost area. However, research objectives directly supporting this issue exist under Wellfield Design (Section 3.1.4) and Reservoir Monitoring (Section 3.1.5).

3.2.4 Well Maintenance

Issue: Geothermal brines are extremely complex chemical solutions. Their effects on well tubulars is a major factor in capital and operating costs.

Level III Objective:

Reduce geothermal production well maintenance costs related to scale deposition by 20 percent by 1992. [H33-01]

3.2.5 Brine Treatment

There are no explicit research objectives for this cost element. However, the objective under Well Maintenance (Section 3.2.4), contains factors that affect this cost element.
3.2.6 Pumps and Fluid Transport

**Issue:** Deposition of scale in surface piping and other fluid transport equipment is a major factor in capital and operating costs for some systems.

**Level III Objective:**

Reduce geothermal field surface equipment costs related to scale deposition by 20 percent by 1992. [H33-02]

3.3 HYDROTHERMAL ENERGY CONVERSION

The Level II Objectives for Hydrothermal Energy Conversion are:

**For binary plants at reservoirs in the temperature range of 150 to 200°C, reduce the cost of power by 17 to 28 percent through improvements in efficiency and in operating and maintenance (O&M), by 1992.**

**For flash plants, reduce the cost of power by 0 to 4 percent through improvements in materials and equipment subject to scaling, corrosion, and other brine-handling requirements, by 1992.**

These cost improvements are exclusive of improvements expected from research associated with the other branches of the cost tree. The main components of these improvements consist of:

- A 31 to 33 percent increase in binary plant efficiency (net brine effectiveness.)
- A 17 to 26 percent reduction in binary plant capital and O&M costs.
- A 0 to 15 percent reduction in flash plant O&M costs.

These changes are due to various improvements in cycle designs and plant components.

The specific research objectives (Level III) which determine the Level II objectives are as follows.

3.3.1 Heat Exchange Cycle

**Issue:** Although the majority of hydrothermal energy is in moderate-temperature brines, the binary electric conversion technology applicable to those brines is largely subeconomic for commercial power generation. More efficient power cycles and equipment would enhance the economics of those brines.

**Level III Objectives:**

Increase net geothermal fluid effectiveness of binary plants by 20 percent by 1992 through the use of improved cycle designs. [H31-01]
Develop a corrosion-resistant and low-fouling heat exchanger tube material costing no more than one-third the cost of high alloy steel tubes by 1991. [H32-03]

3.3.2 Turbine-Generator

Issue: The efficiency of binary power plants can be improved if supersaturated-vapor turbine expansions are proven feasible.

Level III Objective:

Increase net geothermal fluid effectiveness of binary plants by 8 percent by 1992 through the use of supersaturated-vapor turbine expansions. [H31-02]

3.3.3 Heat Rejection Cycle

Issue: Cooling water make-up requirements add substantial expense to geothermal power production, especially at remote desert sites.

Level III Objective:

Reduce heat rejection system cooling water make-up requirements for geothermal power plants by 20 percent by 1991. [H31-03]

3.3.4 Fluid Control & Disposal

Issue: Geothermal brines are complex chemical solutions, and their handling in surface piping and the conversion plant is a major factor in capital and O&M costs. Some combinations of geothermal brines and power cycles produce effluents that currently must be disposed of in hazardous waste dumps at high cost.

Level III Objectives:

Reduce geothermal power plant maintenance and equipment replacement costs related to scale deposition by 20 percent by 1992. [H33-03]

Reduce costs of sludge disposal from geothermal brines by 25 percent or more by 1995. [H33-04]

3.3.5 Non-thermal Products

There are no R&D objectives for this cost area.
3.4 HYDROTHERMAL OTHER OPERATIONS

The only GTD activity in this part of the cost tree falls under cost item Finance, through the Federal Geothermal Loan Guarantee Program, which GTD manages. GTD plans to continue servicing projects that currently have loan guarantees; no new guarantees are expected. Effects from the Program on the average cost of power have not been estimated for this activity. However, the experience gained by the financial community with respect to geothermal power projects could result in a modest reduction in the long-term financing rates for such projects.

3.5 RECENT HYDROTHERMAL TECHNOLOGY IMPROVEMENTS

A few significant improvements in geothermal hydrothermal electric technology have occurred since early 1986, the date of the IM-GEO technology performance and cost baseline.

The hydrothermal technology improvements of which GTD is aware are listed here. They are labeled "LEVEL III ATTAINMENTS," and given identification code numbers starting with "HA" to distinguish them from the hydrothermal research objectives. In the impacts analysis (Appendix B), these attainments are treated as if they are a special subset of the hydrothermal research Level III objectives. When analyzed as a group using the IM-GEO model, the impact of these improvements is a 3.0 to 4.5 percent reduction in the average life-cycle cost of power, from the start of 1986 to the middle of 1988.

3.5.1 Longevity of Downhole Production Pumps

Failure analysis and redesign of downhole production pumps, especially at the Heber (California) field, has shown that the typical service life of line-shaft pumps has risen from about 6 months to about 14 months. The changes in design have reduced the erosive effects of sand on bearings, impellers, and bowls.

Level III Attainment:

The annual service cost for downhole production pumps has been reduced to 43 percent of the 1986 baseline value, effective end of 1987. [HA2-01]

3.5.2 Salton Sea Scientific Drilling Project

This GTD project consisted of drilling and evaluating some of the deeper production zones in the Salton Sea, California, hydrothermal field. The flow testing of the reservoir and preliminary analyses thereof were completed in mid-1988. The new knowledge reveals how the deeper portions of this hydrothermal system behave and should assist future reservoir confirmation efforts.

Level III Attainment:

Reservoir confirmation costs for the Salton Sea area have been decreased by 20 percent, effective mid-1988. [HA1-01]
3.5.3 Cascades/Young Volcanics Exploration Methods

The detection of reservoirs in the Cascades and other young volcanic areas has been hampered by the presence of large cold-water aquifers that disturb the natural thermal regime. The best exploration strategy in such areas is the use of very deep (about 1.5 km) temperature-gradient holes to look below the zone of cold ground water. Three such wells were drilled and evaluated in GTD/industry cooperative projects in 1987 and 1988. The results have had marked impact on exploration and confirmation success in the Cascades region.

Level III Attainment:

The wildcat success ratio for the Cascades region has been increased by 20 percent. [HA1-02]

The general confirmation success ratio for the Cascades region has been increased by 20 percent. [HA1-03]

3.5.4 Treatment of Salton Sea Sludge

Industry experimentation at the Salton Sea field has shown that stripping hydrogen sulfide gas from geothermal brine before it enters the first flash-crystallizer tank markedly reduces the concentration of toxic metal sulfides in the final amorphous silicate sludge. The sludge no longer requires disposal in a hazardous waste dump (RCRA - Class III), resulting in considerable cost savings.

Level III Attainment:

The cost of sludge disposal from flash plants has been reduced to 40 percent of the 1986 nominal cost. [HA3-01]

3.5.5 Beta-C Titanium Production Casing Liners

Engineers have shown by field tests that production liners made of Beta-C titanium alloy should withstand any significant corrosion during a 30-year service life at the Salton Sea field. If carbon steel casings are used, they must be replaced at yearly intervals.

Level III Attainment:

The service life of production liners at the Salton Sea field has been increased to 30 years, from a nominal 1 year, at a nine-fold increase in the cost of the liner. [HA2-02]
4.0 GEOPRESSURED-GEOTHERMAL RESEARCH OBJECTIVES

For a variety of reasons, thousands of oil and gas wells have been abandoned in the Gulf Coast region. Many of those wells penetrated geopressed zones whose resource potential was undervalued or ignored. Indeed, an underlying tenet of geopressed-geothermal research is that the economic lives of some depleted or dry hydrocarbon wells can be extended if those wells are recompleted as geopressed wells.

The technical feasibility of extracting geopressed fluids has been demonstrated at a number of wells in Louisiana and Texas. Research to date has shown that the geopressed-geothermal resource is large and widespread; it contains methane at or close to saturation levels; and it can be produced, used, and the residual brines disposed of with minimal operational and environmental problems. However, several technical and economic questions still remain. These are the focus of the present research program.

The Level I objective for geopressed-geothermal research is to improve the technology for producing energy from the geopressed-geothermal resource at a cost equivalent to 6 to 10 cents/kWh by 1995.a

The energy cost target range (expressed as levelized in 1986 constant dollars) was set by GTD staff through consultation with DOE field R&D managers and other specialists. The objective is founded on the assumption that major technological advances are not required; available petroleum industry technology is adequate to exploit the resource. Given this assumption, the research program focuses on fairly narrow technical issues unique to geopressed resources, such as the burden of handling huge volumes of brine.

Figure 4-1 shows the geopressed-geothermal cost tree, with the elements of GTD's research program indicated by black dots. The R&D is concentrated on:

- Conducting and analyzing flow tests of geopressed wells to ascertain reservoir drive parameters and operating conditions.
- Improving system control and energy conversion technology to optimize energy extraction.

The geopressed cost tree contrasts with the one for hydrothermal (Figure 3-1) in which virtually every element featured research activities. The difference is understandable since the upper level objectives for hydrothermal are based on broad reductions in cost. The geopressed objectives, on the other hand, are focused toward understanding the resource and optimizing its use in the most cost-effective manner. This difference also reflects a limited degree of practical operating experience in the production of geopressed resources as opposed to hydrothermal production. As experience and knowledge are gained, other, more quantitative objectives for technology performance and cost will evolve.

(a) The objective is stated in terms of electricity cost for sake of comparability to Level I objectives across geothermal resource types. In some instances industry may elect to sell only methane and thermal energy.

4-1
Focus of GTD Geopressed-Geothermal R&D Elements upon Electric Project Subsystems

GEOPRESSURED ELECTRIC PROJECT

RESOURCE ANALYSIS
- Exploration
  - Resource Definition
  - Reservoir Evaluation
- Wellfield Design
- Reservoir Monitoring

FLUID PRODUCTION
- Drilling & Completion
  - Stimulation
- Injection
  - Well Maintenance
  - Brine Treatment
  - Pumps & Fluid Transport

ENERGY CONVERSION
- Heat Exchange Cycle
- Turbine - Generator
- Heat Rejection Cycle
- Fluid Control & Disposal
- Non-thermal Products

OTHER OPERATIONS
- Leasing
- Permitting
- Transmission
- General Environment & Safety
- System Optimization
- Finance

Cost Items Affected by GTD Geopressed Program Elements
4.1 GEOPRESSURED RESOURCE ANALYSIS

The Level II objective for Resource Analysis is:

**Improve the understanding of how geopressured reservoirs behave over extended periods of time by decreasing uncertainty in reservoir performance to enable predictions of characteristics (i.e., reservoir size and longevity, hydrocarbon content, salinity) with 90% confidence over a ten-year operating period by 1992.**

The objective for Geopressed Resource Analysis translates into the following objectives (Level III) from the cost tree.

4.1.1 Resource Definition

**Issue:** Numerous oil and gas wells penetrate geopressed horizons, but the operators seldom evaluate the geopressed resource potential. Simplified, inexpensive means of evaluating that potential would increase the likelihood of resource production from wells of opportunity.

**Level III Objective:**

Develop techniques to increase confidence in the ability to locate and evaluate geopressed resources by 1992 such that at least 90 percent of wells recompleted for geopressed-geothermal development are subsequently shown to be economic. [G22-01]

4.1.2 Reservoir Evaluation

**Issue:** The mechanisms driving the production of geopressed fluids are ill-defined. Without knowledge of how and when these mechanisms function, the reliability of geopressed reservoirs will remain uncertain. Long-term production of the Gladys McCall design well has demonstrated that the geopressed reservoir will produce more brine than conventional oil and gas technology would predict. While this result is in a desirable direction, its cause is unknown; premature reservoir depletion might result despite initial good performance. Small quantities of liquid hydrocarbons are produced in geopressed fluids. The composition of the cryocondensates from the Gladys McCall well is primarily aromatics, and the production of condensates and oil has varied due to unknown causes. These variations make the long-term prediction of methane production uncertain. Confident predictions of reservoir productivity will enable better estimates of economic viability.

**Level III Objectives:**

Determine the drive mechanisms for the design well reservoirs by 1991. [G21-01]

Determine source and flow mechanisms for the liquid hydrocarbons and methane being obtained from producing geopressed reservoirs by 1991. [G23-01]
Develop a test procedure which has sufficient accuracy to predict the capability of any geopressured reservoir to be produced for a period five times as long as the test period by 1992. [G21-02]

4.2 GEOPRESSURED FLUID PRODUCTION

The Level II objectives for Fluid Production are:

Prove the long term injectability of large volumes of spent fluid at multiple sites by 1992.

Minimize fluid production operating expenses by 1989.

4.2.1 Injection

Issue: Production of geopressed fluid in commercial quantities requires long-term flow rates of 20 to 40 thousand barrels per day per well. These fluids must be disposed of in an environmentally safe manner.

Level III Objective:

Prove the long term injectability of large volumes of spent fluid into injection wells by 1992. [G11-01]

4.2.2 Well Maintenance

Issue: Pernicious scale has been found in some geopressed wells after fairly short production periods. Such scale could render a geopressed production well effectively useless before the reservoir is exhausted.

Level III Objective:

Develop an effective scale inhibition procedure by 1989. [G11-02]

4.3 GEOPRESSURED ENERGY CONVERSION

The Level II objective for Energy Conversion is:

Improve methods for extracting commercially useful energy from geopressed fluids by 1993.

4.3.1 Heat Exchange Cycle

Issue: Geopressed-geothermal fluid contains chemical (methane) and thermal (heat) energy. Both the methane and heat can be used to produce electricity or the methane can be sold to a pipeline and the heat used for direct use or to produce electricity. If both methane and heat are used for electricity
production, then waste heat from the burning of methane in an engine or turbine can be transferred to a binary fluid for increased energy efficiency in a hybrid system. Hybrid power systems that combine methane and geothermal heat for power generation will produce more electricity than separate power plants using the same amount of natural gas and geothermal heat.

**Level III Objective:**

Develop hybrid conversion technology with thermal efficiency at least 20% greater than that from separate combustion and geothermal power cycles by 1992. [G31-01]

4.4 **GEOPRESSURED OTHER OPERATIONS**

The Level II objective for Other Operations are:

1. Determine environmental acceptability of production and disposal of fluids by 1995.

4.4.1 **General Environment and Safety**

**Issue:** The removal of large volumes of fluid from deep reservoirs may cause surface subsidence while the injection of fluid may cause uplift and induce earthquakes. Leaking surface equipment or well casing could contaminate fresh surface and ground waters.

**Level III Objective:**

Determine if fluids can be disposed of in an environmentally acceptable manner by 1995. [G24-01]

4.4.2 **System Optimization**

**Issue:** Full-time operators are presently required for surface brine handling. Surface equipment at both the Gladys McCall and Pleasant Bayou design well sites have shown susceptibility to corrosion and erosion. Once fully operational, geopressed facilities should be able to function without continuous observation.

**Level III Objectives:**

Develop surface fluid handling facilities (pumps, separators, valves, compressors, etc.) which can be safely operated from a remote monitoring location by 1993. [G11-03]
Develop material specifications, equipment specifications, and maintenance procedures which will allow over 95 percent annual availability with only annual shutdown for routine maintenance by 1993. [G11-04]
5.0 HOT DRY ROCK RESEARCH OBJECTIVES

The technical feasibility of extracting thermal energy from hot, low-permeability rock formations with a man-made fracture system has been established through work at Fenton Hill, New Mexico. A small "Phase I" hot dry rock reservoir was created, enlarged, and flow tested in the 1977-1980 period. A much larger "Phase II" reservoir was created in 1983, and has been flow tested briefly. These accomplishments have been supported by parallel developments in drilling, well completion, and logging instrumentation as well as analytical techniques to understand reservoir behavior. Microseismic fracture mapping and tracer studies, in addition to hydraulic and thermal data, contribute to the reservoir analysis.

The Level I objective for hot dry rock research is to provide the technology to enable industrial hot dry rock projects to generate power at 5 to 8 cents/kWh by 1997.

The energy cost target range (expressed as levelized in 1986 constant dollars) was set by GTD staff through consultation with DOE field R&D managers. Supporting information is available from a variety of independent economic analyses performed by researchers in this country and abroad. The economic feasibility of using hot dry rock resources will depend largely upon sustaining adequate flow at low impedance, minimizing fluid losses, and maintaining controlled thermal drawdown of the man-made reservoir.

Figure 5-1 shows the hot dry rock cost tree, with the elements of the research program indicated by black dots. The R&D is concentrated on conducting and evaluating a long-term flow test of the Fenton Hill Phase II reservoir. Once the test is performed, the results should suggest other, more quantitative objectives for achieving improvements in technology.

5.1 HOT DRY ROCK RESOURCE ANALYSIS

The Level II Objective for Hot Dry Rock Resource Analysis is:

Evaluate the performance of the Fenton Hill Phase II reservoir, by 1993. That performance consists of system operating characteristics, including thermal drawdown, energy output, reservoir impedance, and water consumption.

5.1.1 Resource Definition

Issue: Locating the fractures in a hot dry reservoir must be done before the completion of the second well in the reservoir. Currently the monitoring of hydraulic fracturing operations for purposes of mapping fracture is carried out in adjacent wells. For a commercial system additional observation wells will probably not be economical. Fracture mapping equipment and techniques will have to function reliably with a minimum of two wells.

Level III Objectives:

Improve instrumentation and hardware to locate, measure, and control fracture propagation in hot dry rock reservoirs by 1997. [D21-01]
FIGURE 5-1
Focus of GTD Hot Dry Rock R&D Elements upon Electric Project Subsystems

HOT DRY ROCK ELECTRIC PROJECT

RESOURCE ANALYSIS
- Exploration
  - Resource Definition
  - Reservoir Evaluation
  - Wellfield Design
  - Reservoir Monitoring

FLUID PRODUCTION
- Drilling & Completion
  - Stimulation
  - Injection
  - Well Maintenance
  - Brine Treatment
  - Pumps & Fluid Transport

ENERGY CONVERSION
- Heat Exchange Cycle
- Turbine - Generator
- Heat Rejection Cycle
- Fluid Control & Disposal
- Non-thermal Products

OTHER OPERATIONS
- Leasing
- Permitting
- Transmission
- General Environment & Safety
- System Optimization
- Finance

- Cost Items Affected by GTD Hot Dry Rock Program Elements

5-2
Establish reservoir mapping techniques to locate drilling targets for production wells by 1997. [D21-02]

5.1.2 Reservoir Evaluation

Issue: Although there is confidence that a sufficiently large HDR system can be created, uncertainty continues as to the length of time that a meaningful level of energy can be extracted. Predicting the "size" and life of the man-made reservoir is critical to determining the economic viability of the system. During operation of a HDR system, chemical reactions between the heat exchange fluid (water) and the heat transfer surface (rock) will likely occur. The dissolution and deposition of different mineral species could affect HDR system performance.

Level III Objectives:

Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics by 1993. [D11-01]

Identify water-rock interactions and their effects on flow through a hot dry rock reservoir by 1993. [D22-04]

Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers by 1994. [D22-01]

Confirm modeling of hydraulic and thermal performance of the Phase II system by 1995. [D22-02]

5.2 HOT DRY ROCK FLUID PRODUCTION

The Level II Objective for Hot Dry Rock Fluid Production is:

Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments by 1997.

5.2.1 Drilling & Completion

Issue: Although deep drilling and drilling in very hard rock are becoming more routine in the oil and gas industry, better technology for creating fractures and completing and logging wells under high temperatures can facilitate the development of hot dry rock systems.

Level III Objectives:

Determine means to locate accurately the intersection of fractures with the wellbore by 1995. [D22-03]
5.3 HOT DRY ROCK ENERGY CONVERSION

There is no active R&D in this area. The binary-cycle electric conversion technology being developed under Hydrothermal Conversion Technology (see Section 3.3) will be applicable to hot dry rock projects.

5.4 HOT DRY ROCK OTHER OPERATIONS

The Level II Objectives for Hot Dry Rock Other Operations are:

Determine the environmental acceptability of the technology.

Evaluate the economics of the technology.

5.4.1 General Environment and Safety

Issue: The environmental impacts of hot dry rock energy systems are expected to be minor, but that expectation must be confirmed. Induced seismicity during fracture initiation and subsequent fracture propagation remains speculative. Potential leak-off of pumped fluids into shallow, fresh-water aquifers is also a concern.

Level III Objective:

Verify that the environmental consequences of HDR development are acceptable by 1997. [D12-01]

5.4.2 System Optimization

Issue: Engineering-based analyses suggest that the cost of electricity from hot dry rock systems lies near the competitive economic threshold. Operating data to support these analyses have been lacking.

Level III Objective:

Determine if the performance of the Fenton Hill Phase II reservoir, when considered as a modular unit in a commercial-scale project, could support production of electricity at an economical busbar cost by 1995. [D12-01]
6.0 MAGMA RESEARCH OBJECTIVES

The scientific feasibility of extracting energy from molten rock has been proven by experiments at a shallow lava lake in Hawaii. Technologies are being designed for eventual attempts to recover energy from magma bodies at expected depths of 15,000 to 25,000 feet.

The Level I objective for magma research is to create a technology by which energy could be produced experimentally from magma at an equivalent cost of 10 to 20 cents/kWh by the year 2000.

The energy cost target range (expressed as levelized in 1986 constant dollars) was set by GTD staff through consultation with DOE field R&D managers. The economic feasibility of using magma energy will depend largely on the cost of energy extraction wells and the effectiveness of downhole heat exchange processes.

Figure 6-1 shows the magma project cost tree, with the elements of the current research program indicated by black dots. The R&D is concentrated on:

- Confirming the existence of a magma chamber at a known depth beneath a given drilling site.
- Conducting laboratory tests to better understand the rates at which heat would be transferred from magma to circulating water.
- Designing, fabricating, and testing equipment and materials competent to withstand a magma environment.

6.1 MAGMA RESOURCE ANALYSIS

Surface geophysical measurements have reached a point of diminishing returns for establishing the presence of a magma body. New information at depth is needed to characterize deep anomalous zones accurately. By drilling a staged exploratory well into an active caldera, numerous scientific experiments can be performed that can lead to a better understanding of the evolution and dynamics of magmatic systems, especially when correlated with existing geophysical information.

The Level II Objective for Magma Resource Analysis is:

**Improve the technology for locating and characterizing magma bodies with 90 percent confidence by 1994.**

6.1.1 Exploration

**Issue:** The viability of magma energy extraction currently depends on the ability to find and characterize shallow, accessible magma bodies. Remote geophysical methods are useful in identifying likely targets, but their ability to resolve such targets is limited.
FIGURE 6-1

Focus of GTD Magma R&D Elements upon Electric Project Subsystems

MAGMA ELECTRIC PROJECT

RESOURCE ANALYSIS
- Exploration
  - Resource Definition
  - Reservoir Evaluation
  - Wellfield Design
  - Reservoir Monitoring

FLUID PRODUCTION
- Drilling & Completion
  - Stimulation
  - Injection
  - Well Maintenance
  - Brine Treatment
  - Pumps & Fluid Transport

ENERGY CONVERSION
- Heat Exchange Cycle
  - Turbine - Generator
  - Heat Rejection Cycle
  - Fluid Control & Disposal
  - Non-thermal Products

OTHER OPERATIONS
- Leasing
- Permitting
- Transmission
- General Environment & Safety
- System Optimization
- Finance

* Cost Items Affected by GTD Magma Program Elements
Level III Objective:

Confirm the existence of a shallow magma body with the drilling of an exploratory well by 1992. [M11-01]

Understand the nature of geophysical anomalies at the Long Valley caldera using well observation data by 1992. [M12-01]

6.2 MAGMA FLUID PRODUCTION

The Level II Objectives for Magma Fluid Production are:

Design the first-generation technology needed to extract energy from a magma body by 1997.

Drill, complete, and test a magma energy extraction well capable of producing 30 MWt by 1997.

6.2.1 Drilling & Completion

Issue: Available drilling equipment cannot withstand the higher temperatures, pressures, and volumes of dissolved gases inherent to magma for extended periods of time. Conceptual designs for suitable drilling and completion technology have been formulated, but innovation is still needed to adapt advanced materials and techniques for use in drilling equipment.

Level III Objectives:

Evaluate the performance of materials in corrosive and volatile-rich magma environments for use in drilling tools by 1992. [M23-01]

Design and develop technology capable of drilling into molten magma at temperatures of at least 900°C and total depths of at least 5 km by 1992. [M21-01]

6.3 MAGMA ENERGY CONVERSION

Recent conceptual models indicate that a considerable amount of energy may be extracted from wells drilled into magma bodies. However, many technical questions remain with regard to materials compatibility, heat transfer, convection within the magma chamber, and other matters.

The Level II Objectives for Magma Energy Conversion are:

Determine design specifications of required energy conversion equipment by 1996.

Determine the engineering feasibility of extracting thermal energy from a magma chamber by 1999.
6.3.1 **Heat Exchange Cycle**

**Issue:** Heat transfer in an open magma borehole is expected to take place via a pressurized working fluid (water) flowing through interconnected, permeable fractures in a chilled magma sheath surrounding the borehole. The practicality and efficiency of this energy extraction method remains to be demonstrated.

**Level III Objectives:**

Predict rates for dissolution of silicate minerals and the composition of fluid in a rock-to-water heat exchanger system, and evaluate the potential for loss of permeability due to precipitation of secondary minerals by 1995. [M23-02]

Evaluate heat transfer effectiveness between a magma body and water circulating in the energy extraction wellbore. [M23-03]

6.3.2 **Fluid Control & Disposal**

**Issue:** Large magma bodies are believed to contain substantial amounts of dissolved and free gases under high pressures. The behavior of magma and its associated gases when tapped by a borehole remains speculative. For instance, will molten magma flow or solidify in a borehole? Will degassing occur with explosive force?

**Level III Objective:**

Evaluate magma degassing hazards associated with drilling and energy extraction at Long Valley, California. [M23-03]

6.4 **MAGMA OTHER OPERATIONS**

There are currently no R&D objectives in this cost area.
PROGRAMMATIC OBJECTIVES
OF THE
GEOTHERMAL TECHNOLOGY DIVISION

PART B: IMPLEMENTATION OF OBJECTIVES
IN THE RESEARCH PROGRAM CONTEXT
7.0 RESEARCH PROGRAM ORGANIZATION

The following sections present GTD's Research Objectives in the context of its current research program.

The Work Breakdown Structure of the research program is presented in Section 7.1. Section 7.2 describes the management organization of the research program. Sections 8.0 through 11.0 describe the strategies GTD is using to achieve the Level III objectives and the status of work on these objectives. Major milestones of the work are also included. The organization of these sections follows the hierarchy of the Work Breakdown Structure (Table 7-1), but the text includes cross references to the pertinent objectives.

The identification codes for the Objectives are the same as those used in Part A and are based on the Work Breakdown Structure (Table 7-1).

7.1 WORK BREAKDOWN STRUCTURE

The geothermal research program follows an organizational structure common to all major research programs in the Department of Energy (DOE). This structure possesses a well-defined hierarchy of program elements; in its entirety the structure is referred to as a Work Breakdown Structure (WBS).

The WBS contains various levels below the program. These are, in increasing level of detail: category, task, project, and activity. Under the Geothermal Energy Program there are four research categories which coincide with the four resource types:

- Hydrothermal
- Geopressured-Geothermal
- Hot Dry Rock
- Magma Energy

Each category is made up of several tasks. Tasks cover fairly broad research areas; for the less-developed resource types (e.g., hot dry rock) the tasks are divided between field operations and technology support functions. Projects, and activities resulting from projects, are defined to a level of detail appropriate for effective project management; these are the levels to which the working-level objectives (Level III) usually apply.

The WBS for the Geothermal Energy Program is given down to the project level in Table 7-1.
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<thead>
<tr>
<th>CATEGORY</th>
<th>TASK</th>
<th>PROJECT</th>
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<td>[H] HYDROTHERMAL</td>
<td>[H0] Industrialization</td>
<td>[H01] State-Coupled Grants</td>
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<td>[H02] Direct-Heat Participation</td>
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<td>[H03] Honey Lake Hybrid Power Plant</td>
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<td>Organization</td>
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### Table 7-1

**Geothermal R&D Program Work Breakdown Structure (Cont'd)**

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<td>[M23] Energy Extraction</td>
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7.2 MANAGEMENT OF THE GEOTHERMAL PROGRAM

The responsibilities of DOE Headquarters, Operations Offices, and national laboratories that will be followed in managing the program are highlighted in the following paragraphs.

1. Headquarters

The Geothermal Technology Division has overall management responsibility including policy setting, program planning, budgeting, allocating funds, providing guidance to the field, serving as the focal point for intra- and interagency coordination, required interaction with upper DOE management, and technology transfer.

2. Operations Offices

The Albuquerque (ALO), and Idaho (IDO) Operations Offices are the principal field offices for the Geothermal Program and are responsible for the technical and operational management of specific program tasks.

3. Technical Centers

The following national laboratories are responsible for research in specific subject areas:

- Idaho National Engineering Laboratory
- Lawrence Berkeley Laboratory
- Los Alamos National Laboratory
- Sandia National Laboratories
- Brookhaven National Laboratory

These laboratories undertake the research tasks and technology transfer activities for which they are responsible, coordinate those tasks with the Field Offices and related efforts of other laboratories and contractors, and inform Headquarters of research progress.

7.2.1 Management Structure

The Geothermal Program is managed by the Director of the Geothermal Technology Division (GTD) at DOE Headquarters, Washington, D.C. GTD is responsible to the DOE Assistant Secretary for Conservation and Renewable Energy, and the Deputy Assistant Secretary for Renewable Energy through the Director, Office of Renewable Energy Technologies.

The Director of GTD and his staff provides the centralized leadership necessary to ensure that Geothermal Program activities are consistent with national energy policy, priorities, laws, and directives. Day to day management of technical activities is delegated to the various DOE Field Offices, and through them to the National Laboratories.
7.2.2 Review and Assessments

The program's progress is measured against the objectives stated in this document. A formal procedure for evaluation has been established. It has three parts:

1. Establishment of program milestones and periodic internal review of progress against these milestones.

2. Periodic peer group review of current research.

3. Periodic external review of current research by representatives from industry to consider on how the Federal government can best respond to industry needs.

The evaluation required in item (1) involves periodic program management reviews at different levels within the DOE organization. The primary purpose of this evaluation is to identify management, technical, or policy problems as they arise.

The evaluation required in item (2) is based on critical reviews of specific project accomplishments by researchers. All projects associated with a specific research plan are subject to ongoing review and assessment.

The evaluation required in item (3) is designed to ensure that the program remains on track with respect to meeting industry needs. Reviews conducted by industry groups and university researchers help the program maintain broad-based feedback. They serve as an efficient mechanism for obtaining information on industry viewpoints, on new private sector developments, and other factors that should properly be a part of future year programming decisions.

7.2.3 Technology Transfer

Technology transfer is an integral program activity. The Geothermal Program's investment in research activities is of little value unless the results are promptly transferred to the private and public sectors. Systematic means are in place to assure that geothermal developers, utilities, materials and components manufacturers, and other members of the geothermal industry readily acquire and implement the output of the Geothermal Program research effort.
8.0 HYDROTHERMAL RESEARCH CATEGORY

8.1 TASK: Reservoir Technology

8.1.1 PROJECT: Reservoir Analysis

LEVEL III OBJECTIVES:

Reduce the number of wells needed to define the resource by 33% by 1992. [H11-01]

By increasing the accuracy and precision of information required for models of reservoir characteristics and performance, decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 10% by 1992. [H11-02]

Strategy: GTD researchers will develop an improved understanding of the physical and chemical processes in hydrothermal systems through field case studies of operating geothermal systems in the U.S. and elsewhere. That understanding will include improved geological, geochemical, geophysical, hydrological, and reservoir engineering models of hydrothermal systems. Emphasis will be placed on methods to detect and map fractures and permeable zones. New geophysical techniques (e.g., borehole-to-borehole and surface-to-borehole methods) will increase drill hole information and extend investigations beyond the drilled hole. The sensitivity and resolution of geophysical methods for mapping geothermal systems will be improved. And improved well testing methods and interpretation techniques to determine reservoir characteristics will be developed.

Status: Seismic and electromagnetic methods are being evaluated for their effectiveness in locating and characterizing fractures. Vertical seismic profiles provide information about the orientation of fractures, their spacing, and other parameters. Methods are being developed to interpret vertical seismic profiles. New instrumentation provides greater sensitivity to well testing measurements and provides geoscience data that were previously not available. Improved analysis of well tests uses all of the data to evaluate the reservoir. Design and construction is underway for a laboratory facility to study multiphase flow in fractures with rough walls.

Milestones:

1. Completed comparison of reservoir evaluations based on old porous medium models versus improved fracture medium representation. 9/88

2. Develop analytical solutions for wellbore heat transmission in layered formations, and develop methods for heat sweep calculations in fractured reservoirs. 8/89

3. Incorporate laboratory measurements of multiphase fracture flow into numerical model of reservoir production. 7/90
LEVEL III OBJECTIVES:

Reduce uncertainties in predictions of reservoir capacity by 15% by 1992. [H11-03]

By improving reservoir evaluation methods, decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 15% by 1992. [H11-04]

Reduce the number of wells needed to evaluate a reservoir by 10% by 1992. [H11-05]

Strategy: The strategy seeks to improve numerical, conceptual, and physical models for heat and fluid transport, and chemical reactions in geothermal reservoirs. GTD researchers will conduct basic research on reservoir physics to determine and quantify fundamental parameters that control the behavior of geothermal systems and wells (e.g., multiphase flow in fractures, chemically and mechanically coupled processes). New and improved methods for obtaining and analyzing well data will be explored. Long-term field case studies, as joint DOE-industry projects, will be established where possible. The aims are to: increase experience in wellfield behavior; facilitate obtaining good quality data; verify and validate reservoir models; improve models that simulate and predict reservoir and well behavior. The emphasis on chemistry of rock-water interactions in transport models will increase. The intent is to reduce the cost of these computer simulations and verify them against long-term reservoir production data.

Status: Information gathered through several types of well testing is being used in numerical models to predict reservoir behavior in response to fluid withdrawal. Well testing methods and the required instrumentation are being developed to provide critical data for use in predictive models. Actual operating histories are used to verify existing reservoir models and to develop more accurate prediction capabilities. New approaches to the analysis of well tests have provided some of the parameters needed in improved models. Long-term production and injection testing was conducted jointly with Oxbow Geothermal in Dixie Valley. Cost-shared research with industry allows access to operating fields where new methods and equipment can be tested. (Also see Brine Injection Project.)

Milestones:

1. Solved the pressure transient problem in complexly shaped reservoirs. 8/88

2. Test the derivative decline curve method to evaluate reservoir performance. 8/89

3. Compare injection tracer results and the pressure distribution to field production. 6/90

8-2
8.1.2 PROJECT: Exploration Technology

LEVEL III OBJECTIVES:

Increase the success ratio of wildcat exploration wells, especially in frontier areas such as the Cascades, by 20% by 1992. [H12-01]

Devise better methods and strategies for discovering hidden hydrothermal systems, and for exploring the deep extensions of known systems so that industry can locate three such hidden reservoirs by 1992. [H12-02]

Strategy: Through the study of active and fossil hydrothermal systems, a better understanding of the global, regional, and local igneous and tectonic processes that generate hydrothermal resources and control their locations will evolve. GTD researchers will obtain a better understanding of the physical and chemical processes that take place in hydrothermal systems. From an improved understanding of known hydrothermal systems, better generic models of hydrothermal systems will result, and these models can be used to develop new exploration methods, techniques, and strategies. GTD researchers will develop new rock, water, and gas geochemical techniques to identify hidden hydro-thermal systems. They will improve regional geophysical methods and interpretive techniques for exploring to depths greater than 2 km. Cost-shared R&D between DOE and industry, especially in frontier areas, will be pursued.

Status: GTD has worked with industry to drill and core several holes to depths of 1.2 to 1.5 km to obtain accurate heat flow values. Geophysical logs and surface electromagnetic surveys are being examined to determine which correlates best with critical parameters of geothermal reservoirs. Low resistivity has been correlated with both low-temperature and high-temperature alteration mineralogy, and physical measurements of cores show subtle differences in the electromagnetic response. Combinations of several geophysical methods are being tested to identify characteristics of high-temperature geothermal systems, and to reduce the ambiguity of individual methods. New equipment and interpretation methods are being developed for magnetotelluric surveys, electromagnetic measurements, remote sensing for structural analysis, and conceptual models of geothermal systems. New geochemical geothermometers will be studied through laboratory and field studies. New refinements in sampling and analysis of surface water samples will be investigated.

Milestones:

1. Field tested new magnetotelluric system. 9/88
2. Evaluate and calibrate mica-mica geothermometer. 5/89
3. Evaluate new magnetotelluric interpretation model. 8/89
4. Field test new electromagnetics systems. 6/90
5. Evaluate breakout model for interpretation of stress directions. 8/90
8.1.3  PROJECT: Brine Injection

LEVEL III OBJECTIVES:

Increase the success ratio of in-fill wells for production and injection i.e., decrease the dry-hole ratio for in-fill wells for production and injection by 33% by 1992. [H13-01]

Improve methods for positioning and designing geothermal production and injection wells in order to reduce the aggregate cost of wells by 15% by 1992. [H13-02]

Strategy: The strategy involves improving methods for detecting and mapping fractures and permeable zones in order to optimize the siting of wells in a geothermal field. This involves increasing the reliability and reducing the cost of downhole instrumentation for use in high-temperature wells up to 350°C. In comparative field case studies of reservoirs, include an emphasis on drilling and completion information. Other emphases will include: methods to couple well-bore models to reservoir numerical simulation models, improved well designs using such integrated simulators, and better methods to monitor well performance.

Status: Theoretical and numerical models have been used to identify geophysical methods to map fractures from the surface and between boreholes. Several of these methods look promising for field testing. Instruments using fiber-optics are being investigated for long-term downhole monitoring of pressure, temperature, and water chemistry in high-temperature wells. Tracer testing has proven useful in one field for the selection of optimum sites for production and injection wells.

Milestones:

1. Construct borehole to borehole resistivity and electromagnetic systems. 9/89

2. Test integrated well-bore and reservoir model. 5/90

3. Field test subsurface resistivity system. 6/90

4. Field test subsurface electromagnetic system. 8/90

5. Field test fiber-optics monitoring system. 3/91

LEVEL III OBJECTIVES:

Improve reservoir monitoring methods to decrease uncertainties in forecasting short-term and long-term reservoir changes in fluid temperature, pressure, flow rate, and chemistry by 10% by 1992. [H13-03]

Reduce the number of low-flow and short-lived production and injection wells
Reduce the number of low-flow and short-lived production and injection wells drilled after production begins by 15% by 1992. [H13-04]

Improve the efficiency of the production and injection schemes to reduce the number of make-up wells by 10% by 1992. [H13-05]

Reduce uncertainties related to long-term reservoir changes in fluid temperature and injection breakthrough by 10% by 1992. [H13-06]

Reduce the number and severity of unexpected environmental problems, especially those related to potential seismicity and subsidence. [H13-07]

**Strategy:** In comparative field case studies of reservoirs, emphasize collection of data and operating experience with respect to long-term field behavior. Joint DOE-industry research projects will be conducted to document details of changes in producing fields. Develop low-cost tracers for liquid- and gas-phase flow and new methodologies for conducting and interpreting tracer tests. Methods for monitoring subsurface changes due to production, such as encroachment of cold water, and new geochemical methods for detecting changes in the reservoir as production proceeds will be pursued. Other studies will seek methods to predict and track chemical and thermal fronts in the reservoir.

**Status:** Numerical models have been developed to predict the results of various sites for injection wells, and these models are being tested with field data. Chemical tracer tests are used to determine actual flow paths through a reservoir and to determine parameters needed for modeling. Geophysical methods are being tested for the possibility of tracking injected fluid. (Also see Reservoir Technology – Reservoir Analysis.)

**Milestones:**

1. Interpret Dixie Valley tracer test to predict chemical front movement through reservoirs. 7/89
2. Evaluate field analysis techniques for chemical tracers. 3/90
3. Integrate new tracer interpretation techniques with reservoir modeling for more refined fluid flow interpretation. 7/90

**8.2 TASK:** Hard Rock Penetration

**8.2.1 PROJECT:** Lost Circulation Control

**LEVEL III OBJECTIVE:**

Reduce costs associated with lost circulation episodes by 30 percent by 1992. [H21-01], c.f., [H32-01]

**Strategy:** Approaches to controlling lost circulation include: development of lost circulation materials, pumpable setting fluids, polyurethane foams, cements,
and placement of lost circulation materials. Alternative methods for lost circulation control and recovery will be pursued to reduce drilling time lost in diagnosing and ameliorating lost circulation problems. The R&D efforts include: developing, through analysis and experiments, a basic understanding of the two-phase flow phenomena that control fracture plugging; evaluating the high-temperature plugging characteristic of specific lost circulation materials; characterizing lost circulation hydraulics and zones; and conducting full-scale laboratory and field tests for foams and pumpable setting fluids.

**Status:** Many potential lost circulation materials have been tested for high temperature and pressure durability and fracture plugging capabilities. Recent tests indicate that lost circulation material performance is often improved by using a mixture of different materials, sizes, and shapes. Foam loss circulation tools were built and operated successfully downhole, but additional development of a suitable high temperature and pressure polyurethane foam is required. A pumpable cement test facility is being designed to duplicate typical field conditions, with testing of cements to start in 1989. Characterizing loss circulation zone work includes developing wellbore hydraulics models for evaluating drilling fluid losses, developing hardware/software to acquire and analyze on-site drilling data, and comparing hydraulic model predictions with physical attributes.

**Milestones:**

1. Develop field procedures to measure characteristics of lost circulation zones. (9/89)
2. Design and test new geothermal loss circulation materials. (8/89)
3. Field-test lost circulation materials. (8/90)
4. Complete final report on loss control materials testing. (9/91)
5. Correlate analysis, experimental data, and field data. (6/92)
6. Develop expert system to characterize and treat loss zones. (12/92)

**8.2.2 PROJECT: Rock Penetration Mechanics**

**LEVEL III OBJECTIVE:**

Reduce costs of deep wells and directionally drilled wells by 10 percent by 1992. [H22-01]

**Strategy:** Determination of the optimum bottom hole assemblies while drilling to reduce deviations and improve drilling rates is highly desired by the oil, gas and geothermal industries. Knowledge of bottom hole forces is important because it measures the environment directly, allows better tool design, permits optimum selection for assembly components and drilling parameters, and aids in predicting the trajectory. Preliminary measurement while drilling systems have
cut drilling times by up to 50 percent. GTD will develop advanced data transmission for measurement while drilling systems and develop incremental advancements in drilling and coring systems.

Status: An acoustical data telemetry system currently under development is designed to provide a reliable system that will accommodate data transmission rates of about 100 bits per second, up from the commercial mud pulse systems which operate between two and four bits per second. Initial analysis and lab model tests indicate very good comparisons are achieved between theory and experiment. A scale model was used to evaluate designs for the sending and receiving transducers of the telemetry systems. The results indicate the existence of frequency bands which are virtually free of attenuation and suitable for data transmission at high bit rates. Scale models of the transmitting and receiving transducers designed during FY 88 will be built and tested. Two types of transmitting transducers will be constructed: one to operate within the drill string and the other within the drill collar. An industry service company has expressed interest in a joint-venture to develop a full-scale field test of the data telemetry system.

Deep, hot formations create problems for convention drilling fluids, drill strings, and hole stability. A needed component in high-temperature drilling/coring systems is insulated drilling pipe. The use of insulated drill pipe will keep the fluid and tubulars cooler than their critical values. Calculations have indicated feasibility, and the concept will be tested using prototype joints of insulated pipe. Working with industry suppliers, two designs were completed for insulated drill pipe in FY 88. Prototype pipe will be purchased and the thermal performance and mechanical strength will be evaluated in the laboratory.

Milestones:

1. Complete lab evaluation of insulated drill pipe. (8/89)
2. Test insulated drill pipe in Magma exploratory well. (10/90)
3. Complete full scale design of acoustical data transmission system. (3/90)
4. Complete lab test of acoustical data transmission system. (12/91)
5. Complete field test of acoustical data transmission system. (12/92)
6. Transfer data transmission system to service company. (9/93)

8.2.3 PROJECT: Instrumentation

LEVEL III OBJECTIVES:

Decrease cost of drilling production-related geothermal wells by about 5 percent by 1992, through better identification of fractures. [H23-01]
Strategy: At The Geysers, some wells drilled as close as 100 to 300 feet from a commercial producer have failed to encounter fractures for commercial production. This inability to identify and locate fractures near a wellbore indicates a need for a high-resolution, fracture-mapping technique. Once fractures can be located, directional drilling can turn a dry hole into a producer. Conventional seismic techniques do not provide the necessary resolution. A radar fracture-mapping tool and flow meters will be developed to improve the location of fracture zones near a well-bore, and thereby improve more accurate completion-zone siting.

Status:
A wireline radar fracture-mapping tool is under development. A prototype tool with high-energy-pulse and directional capabilities has been assembled. The tool uses directional antennas for both the transmitter and the receiver to provide both the distance (1-foot accuracy) and direction of a fracture in a downhole application. Recent tests conducted in a rock quarry and a lake demonstrated that the tool does perform as predicted.

A second generation tool will be designed using a modular concept with variable antenna spacing, a diameter of less than 5 inches, and an upgraded electrical system. Additional field tests will be conducted to evaluate the tool's directional characteristics and ability to discriminate a reflecting surface in a fractured formation. Cost sharing with the private sector will be sought for final development.

Milestones:

1. Report laboratory test results and evaluate performance of prototype tool. (3/89)
2. Complete design of second generation tool. (12/89)
3. Complete construction of second generation tool. (9/90)
4. Field test second generation tool in geothermal wells. (10/91)
5. Transfer radar fracture mapping tool to industry. (6/92)

LEVEL III OBJECTIVE:

Decrease the uncertainties in measurements of downhole and well head temperature, pressure, and flow measurements for moderate temperature reservoirs by 25 percent by 1990. Decrease the uncertainties for similar measurements at reservoir temperatures greater than 250°C, by 50 percent by 1992. [H23-02]

Strategy: Currently, pressure and flow rate measurements in geothermal wells suffer accuracy and reliability problems due to the high temperature and corrosive fluid environment found downhole. Downhole flow measurements using propeller and turbine type flow meters often fail due to the high flow rates and erosion/corrosion. All downhole measurements above 300°C are
difficult since this is the practical upper limit for wireline cables. The strategy involves development of advanced downhole logging instruments capable of withstanding hydrothermal environments.

Status: A series of "slickline" tools was developed to measure temperature, pressure, and flow in the DOE Salton Sea Scientific Drilling Project at temperatures up to 400°C. These tools, which store data downhole for later retrieval at the surface, included mechanical Kuster tools for measuring temperature, pressure, and flow; a temperature and pressure tool built around an electronic memory; and a timing and control unit to power a downhole sampler. The electronic tools with downhole memory were found to offer the most promise for future development. The concept of self-contained downhole memory tools will be expanded to develop a modular downhole instrumentation system. This modular system will be designed to meet future instrumentation requirements for the magma energy exploratory well (temperature up to 500°C). Design of the microprocessor and memory module is underway and testing will start in 1989. Also, fiber optic cables and sensors will be investigated for higher temperature capabilities.

Milestones:

1. Design a versatile downhole memory unit capable of large data storage for operation at 400°C. (9/89)
2. Select three passive flow measurement techniques that can be used for downhole flow logging. (3/90)
3. Design temperature, pressure, gamma, and collar locator measurement instruments and test in the laboratory. (12/90)
4. Construct new passive flow measurement instruments and test in the laboratory. (7/91)
5. Field test new instruments. (8/92)

8.2.4 PROJECT: Geothermal Drilling Organization

LEVEL III OBJECTIVE:

Develop and transfer other related technology to effect an additional 5 percent reduction in well costs by 1990 and 10 percent by 1992. [H24-01]

Strategy: Use the Geothermal Drilling Organization, a non-profit research consortium, to develop improved technology that can be transferred quickly to industry.

Status: The Geothermal Drilling Organization (GDO), a non-profit consortium of industrial firms, and DOE jointly fund projects which are designed to transfer technology to industry vendors. GDO members often become extensively involved in the field-test phase of these projects to aid shifting of...
the technology to a vendor. Projects currently include: acoustic borehole televiewer, foam lost circulation tool, downhole air turbine, and high-temperature elastomer products.

Acoustic borehole telviewers are used in water/mud-filled wells to map formation fractures in open boreholes and to inspect internal casing surfaces in cased wells. Two high-temperature telviewers have been fabricated and were initially tested successfully in a 4,000-foot well at 260°C. After additional testing, a logging company will be able to adopt the technology and offer it to the geothermal industry.

Two downhole foam lost circulation tools have been assembled and field-testing has been initiated. In field and lab tests a two-component, rigid urethane foam has been shown to be ineffective in bridging and cementing unconsolidated material. Development of an acceptable foam is continuing.

Downhole air turbines capable of operating up to 260°C have been developed and will be field tested at The Geysers. They were designed to improve directional drilling capabilities and drill with air in production areas where lost circulation would be a major problem. Four field tests were completed at The Geysers in 1988, several modifications have been completed and a third prototype is being designed with testing planned for March 1989.

High-temperature elastomers will be fabricated and tested for use as drill pipe protectors, rotating head seals and blow-out preventors.

Milestones:
1. Complete field-testing of downhole air turbine at The Geysers. (9/89)
2. Field test and evaluate foam lost circulation materials. (10/90)
3. Develop and test drill pipe protectors. (12/89)
4. Achieve transfer of borehole televiewer to vendor. (4/89)
5. Develop and test rotating head seals and BOP elements. (9/89)
6. Develop and test blow-out preventer tool. (5/91)

8.3 TASK: Conversion Technology

8.3.1 PROJECT: Heat Cycle Research

LEVEL III OBJECTIVE:

Increase net geothermal fluid effectiveness of binary plants by 20 percent by 1992. [H31-01]
Strategy: The strategy calls for increasing net geofluid effectiveness in two ways. First, improving the accuracy of heat exchanger performance ratings will reduce losses and costs due to over- or under-sized equipment. Second, several process-oriented improvements such as use of supercritical vaporizations, countercurrent integral condensation with recuperations, and advanced types of working fluids will substantially improve cycle efficiencies.

Status: The work on improving effectiveness is done at the Heat Cycle Research Facility (HCRF) located in California's Imperial Valley. Testing completed thus far has confirmed design methods for supercritical vaporization of mixed working fluids; current testing is investigating countercurrent integral condensation.

Milestones:
1. Complete supercritical cycle testing; prepare report. (5/90)
2. Issue final report. (5/92)

LEVEL III OBJECTIVE:

Increase net geothermal fluid effectiveness of binary plants by 8 percent by 1992 through the use of supersaturated vapor turbine expansions. [H31-02]

Strategy: GTD researchers will determine effects of supersaturated vapor expansions on radial-inflow, reaction turbine performance in laboratory and field tests.

Status: This research so far has been confined to the laboratory, but in FY 1989 it will go to the field with the addition of a two-phase nozzle to the Heat Cycle Research Facility. A small radial inflow turbine will be obtained from a commercial manufacturer and tested under operating conditions not presently considered to be part of the normal operating envelope.

Milestones:
1. Install 2-D nozzle and reaction turbines at HCRF. (12/88)
2. Complete metastable supersaturated vapor expansion testing; report results. (5/90)
3. Issue final report. (9/92)

LEVEL III OBJECTIVE:

Reduce heat rejection system cooling water make-up requirements for geothermal power plants by 20 percent by 1991. [H31-03]

Strategy: The research is aimed at expanding the useful geothermal resource base especially at remote desert sites. Heat rejection schemes that require
less cooling water make-up without incurring significant performance penalties will be first the subject of theoretical studies, then laboratory experiments, and finally field-testing to establish their feasibility.

**Status:** The initial screening of advanced heat rejection schemes has been limited to theoretical analysis of the Kalina cycle with mixed composition working fluids.

**Milestones:**

1. Completed report on applicability of mixed fluid Kalina cycles. (12/88)
2. Complete system study for the Advanced Heat Rejection System. (5/89)
3. Complete research and report results for the Advanced Heat Rejection System. (9/91)
4. Issue final report. (9/91)

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**8.3.2 PROJECT: Materials Development**

**LEVEL III OBJECTIVE:**

Reduce costs associated with lost circulation episodes by 30 percent by 1992. [H32-01], c.f., [H21-01]

**Strategy:** The strategy is to improve the effectiveness of materials used to control lost circulation episodes that occur during well-drilling and completion operations. Currently, the cost of correcting lost circulation constitutes about 10 percent of the cost of typical wells. GTD researchers will develop rapid-curing, high-temperature cements that can be introduced through the drill pipe into lost circulation zones. Elimination of the need to remove the drill string will reduce downtime and aid in the location of the fractured zone.

**Status:** To date, two promising formulations have been identified and characterized in the laboratory. Larger-scale tests are planned for the period FY 1989–1990 in a cooperative effort with private industry.

**Milestones:**

1. Completed optimization of formula. (12/88)
2. Complete mud displacement test as a cooperative effort with industry. (8/89)
3. Use in well demonstration. (1/90)
4. Issue final report. (9/90)
LEVEL III OBJECTIVE:

Develop well-cementing materials with a service lifetime of 30 years at 400-600°C by 1991. [H32-02]

Strategy: The strategy is to improve the effectiveness of geothermal well completion procedures by the development of CO₂-resistant, lightweight, high-temperature cements with twice the lifetime of existing cements. These improvements will help to transfer limitations on well life from materials constraints to reservoir productivity.

Status: Work is being performed as a cooperative research effort with the New Zealand Department of Scientific Research (DSIR). GTD researchers develop the cement formulations and perform physical, chemical, and mechanical evaluations. DSIR conducts the downhole tests in wells at their Mokai and Rotokawa geothermal fields.

Milestones:

1. Identified best candidate CO₂-resistant lightweight cements based upon laboratory evaluations. (10/88)
2. Complete downhole tests at 300°C in brine containing low concentrations of CO₂. (4/89)
3. Complete one-year downhole test in brines containing high CO₂ concentrations. (6/90)
4. Test cement in a demonstration well. (1/91)

LEVEL III OBJECTIVE:

Develop a corrosion-resistant and low-fouling heat exchanger tube material costing no more than one-third the cost of high alloy tubes by 1991. [H32-03]

Strategy: The strategy is to improve the net geothermal fluid effectiveness of binary plants by the development of high-thermal-conductivity, corrosion-resistant, nonmetallic liners on carbon steel substrates. Heat exchanger effectiveness can be improved with low-cost, corrosion-resistant, low-fouling heat exchanger tubing. Tubing formulations based on polymer concrete materials are being developed and fabricated for testing. The intent of this research is to minimize cost while maintaining adequate thermal conductivity and resistance to chemical attack from geothermal brine.

Status: The development work has so far been performed in the laboratory, but in late FY 1989 prototype 20-foot-long tubes with polymer concrete lining will be field-tested as part of a cooperative effort with the Heat Cycle Research Project (see p. 8-11). Corrosion and flowing rates will be measured at the temperatures and fluid velocities typical of binary plants.
Milestones:

2. Complete field measurements of HX performance. (6/89)
3. Complete field-testing of multitube brine/organic HX. (9/90)
4. Issue final report. (1/91)

8.3.3 PROJECT: Advanced Brine Chemistry

LEVEL III OBJECTIVES:

Reduce geothermal production well maintenance costs related to scale deposition by 20 percent by 1992. [H33-01]

Reduce geothermal field surface equipment costs related to scale deposition by 20 percent by 1992. [H33-02]

Reduce geothermal power plant maintenance and equipment replacement costs related to scale deposition by 20 percent by 1992. [H33-03]

Strategy: The significant changes in temperature and pressure that occur during the brine production, energy utilization, and brine disposal stages of geothermal plant operations may result in chemical disequilibria. If the brine becomes sufficiently supersaturated, significant scale formation may take place, resulting in production or injection well sealing and/or plugging of plant equipment. Chemical models will be designed to determine the degree of chemical disequilibrium and the amount of scale formation to be expected during plant operation.

These same models also are useful in predicting chemical problems that may occur when spent brines are disposed of by injecting them into chemically incompatible rock formations. Modeling can be used to determine the degree of thermodynamic incompatibility between an injected spent brine and the receiving formation. Consequently, the efficiency of all stages of geothermal plant operations can be enhanced by model simulation; when fully developed, models will provide the geothermal industry with valuable process design tools that can be used to control the plant's chemistry and avoid plant failures due to scaling and/or corrosion.

Status: A dynamic model of brine chemistry thermal equilibria and kinetics is being formulated which synthesizes the observed behavior of major ionic species at temperatures up to 250°C and enables reliable estimates of scaling potential.

Through current research, a model of brine chemistry in a system composed of sodium, calcium, chlorine, sulfate, carbonate, carbon dioxide, and water has almost been completed from 25°C to 200°C. Comparison of the model with
laboratory data has shown the model to be highly reliable. The model will become an even more valuable cost-saving tool as other species are added. These include silica, methane, and hydrogen sulfide.

Milestones:
1. Incorporate solubility data for calcite in sodium bicarbonate solutions. (12/88)
2. Include silicon dioxide aqueous species and solid amorphous silicon dioxide in model. (7/89)
3. Produce solubility model for methane in sodium chloride brines. (9/90)
4. Add existing hydrogen sulfide and bisulfate data to model. (7/91)

LEVEL III OBJECTIVE:
Reduce costs of surface disposal of sludge from geothermal brines by 25 percent or more by 1995. [H33-04]

Strategy: Brines from the Salton Sea KGRA in the Imperial Valley may contain total dissolved solids up to 350,000 ppm. These hypersaline brines lead to the generation of geothermal solid wastes in power plants. The wastes must be analyzed for regulated metals, and if found hazardous, they must be disposed of off-site in an approved waste management facility. Currently, the disposal of these wastes can cost up to $1 million per year for a 50-MWe geothermal flash power plant operating in the Salton Sea KGRA. Therefore, the development of low-cost, environmentally acceptable means for disposing of toxic geothermal residues will be pursued.

The strategy relies on the use of microbes, since microorganisms can interact with metals by several mechanisms such as surface adsorption, oxidization, reduction, and solubilization and/or precipitation. Through these mechanisms, biochemical processes will be used to concentrate and remove toxic metals from geothermal sludges. GTD researchers will develop microbial treatments of toxic substances to enable disposal of sludge residues as nonhazardous wastes.

Status: Using waste samples supplied by various geothermal developers, small laboratory experiments have been conducted using biochemical processes. A number of microorganisms have been studied that have the ability to efficiently remove metals such as copper, chromium, zinc, lead, and arsenic from geothermal wastes. Research has also been conducted with mixed cultures; preliminary results indicate that the metal removal efficiency can be greatly enhanced by this procedure. Experiments at larger scales are planned in the future to study scale-up kinetics.
Milestones:

1. Scale up experiments to 10-gallon range using best candidate organisms. (12/88)
2. Assess optimization experiments using thermophilic organisms. (9/89)
3. Evaluate scaled-up parameters for kinetic reactions using single and mixed organisms. (12/89)
4. Assess the economic feasibility of a biochemical process. (12/91)
5. Undertake a proof-of-concept experiment in cooperation with industry. (10/93)
9.0 GEOPRESSURED-GEOTHERMAL RESEARCH CATEGORY

9.1 TASK: Well Operations

9.1.1 PROJECTS: Pleasant Bayou Reservoir; Gladys McCall Reservoir; Hulin Reservoir

LEVEL III OBJECTIVE:

Prove the long-term injectability of large volumes of spent fluid into injection wells by 1992. [G11-01]

Strategy: Geopressed brine is produced in large volumes of 20,000 to 40,000 barrels per day from a single well. After the dissolved methane is removed from the brine by gravity separation and the thermal energy is recovered, the brine must be disposed of. This is accomplished by adding scale inhibitors to prevent scaling, filtering the brine, and injecting the spent brine into a normally-pressured formation that is shallower than the producing formation, via an injection well. The spent brine should be at a sufficiently high pressure to allow injection without the use of pumps. The injection well pressure will be monitored for pressure changes that may indicate formation or perforation plugging. As needed, remedial action will be taken.

Status: The injection well at Gladys McCall was drilled originally as a hydrocarbon exploratory prospect in 1965. The well was plugged back to 3,460 feet, and recompleted with perforations between 3,050 to 3,500 feet. A minor problem encountered was the sanding up of the injection well because of sand back-flowing into the wellbore due to a leaking check valve during a shut-in period. From October 1983 through October 1987, 27 million barrels of brine were injected into the Gladys McCall disposal well in Cameron Parish, Louisiana.

The injection well at the Pleasant Bayou site was plugged back and perforated from 6,226 to 6,262 feet. The well has been used to dispose of about 4 million barrels of brine from 1980 through 1983. This injection well will be used for disposal of brine from a long-term flow test from 1988 through 1990.

Disposal of large volumes of brines using injection wells is proving feasible. Operators of such injection wells can minimize operating costs and prevent potential problems by using inhibitors to prevent scaling, filtering the brine to prevent particulates from plugging the receiving formation, and preventing back flow into the injection well. Additional operating experience in other geopressed reservoirs, especially Hulin, remains to be gained.

Milestones:

1. Began long-term flow testing of Pleasant Bayou well. (6/88)
2. Complete flow testing of Pleasant Bayou well. (7/90)
3. Begin flow testing of Hulin well. (8/89)
4. End flow testing of Hulin well. (10/91)
LEVEL III OBJECTIVE:

Develop an effective scale inhibition procedure by 1989. [G11-02]

Strategy: Calcium carbonate scale in surface facilities piping is easily handled by injecting scale inhibitor into the flow lines. However, scale in the producing formation or in the production well tubing is a more difficult control problem. The coating of the production tubing with scale decreases the flow rate. Scale in the production tubing also degrades the wellhead pressure data making interpretation difficult or meaningless. Scale in the producing formation increases the skin effect and may result in plugging of the formation. Injection and backflow of inhibitors will be closely controlled and monitored during well tests. Long-term scale control will be monitored; periodic inspections will be conducted to check performance of materials and equipment used in the surface facilities.

Status: The first attempts at phosphonate inhibitor squeezes into the producing formation at Gladys McCall were unsuccessful because downhole plugging prevented pumping all the inhibitor into the formation. The problem was solved by: (1) using a brine spacer ahead of the inhibitor to force the formation water away from the wellbore, and (2) injecting good quality water that had been filtered to remove iron hydroxide. The first successful phosphonate inhibitor squeeze in 1985 allowed the production of 5.4 million barrels of brine without any scaling on the high-pressure portion of the surface facilities. A simplified phosphonate inhibitor treatment was designed and used at Gladys McCall in 1986. A total of 13 million barrels of brine was produced after the second treatment without an indication of scaling in the downhole production tubing.

An ongoing test of the simplified phosphonate inhibitor began at the Pleasant Bayou site in 1988. Coupons in the surface facilities brine stream at Pleasant Bayou are examined on a regular basis to monitor any scale formation. If possible, the inhibitor will be verified during tests of the Hulin reservoir.

Milestone:

1. Inject phosphonate inhibitor into rock formation at Hulin (repeat as necessary). (9/89)

LEVEL III OBJECTIVE:

Develop surface fluid handling facilities (pumps, separators, valves, compressors, etc.) which can be safely operated from a remote monitoring location by 1993. [G11-03]

Strategy: A large portion of the cost of operating surface facilities is the labor needed to oversee the system. Automating the surface facilities so that no on-site personnel are required would result in significant cost savings. Instrumentation and control companies will design and build automated control systems for the production of brine, separation of gas, and disposal of spent brine. Those systems will be verified with field tests.
Status: During the design and construction of the Pleasant Bayou surface facilities, a file was maintained detailing how to automate the surface facilities. If surface facilities are to be built at the Hulin site, this information will help to design them. Instrumentation and control companies will be asked to design automated control systems for the production of brine, separation of gas, and disposal of waste brine. Field testing at the Hulin site will determine the feasibility of fully automated surface facilities. Automated surface facilities are tentatively planned for the Hulin well site if the reservoir is capable of supporting long-term flow testing.

Milestones: TBD

LEVEL III OBJECTIVE:

Develop material specifications, equipment specifications, and maintenance procedures which will guarantee over 95 percent annual availability with only a two-week annual shutdown for routine maintenance by 1993. [G11-04]

Strategy: High availability of surface facilities allows for the effective use of the facilities and results in increased revenues. Researchers will use the experience gained from the operation of surface facilities at existing sites to develop materials specifications, equipment specifications, and maintenance procedures that will guarantee high availability.

Status: The surface facilities at Gladys McCall operated with greater than 98 percent availability from February 1986 through October 1987. Piping at the Pleasant Bayou surface facilities has been designed to reduce areas of erosion, and stainless steel piping has been used in areas with high erosion rates. Availability at Pleasant Bayou should equal or exceed the availability at Gladys McCall. If possible, the results will be verified by tests at Hulin.

Milestones:

1. Constructed Pleasant Bayou surface facilities and began flow testing. (6/88)


9.2 TASK: Geoscience & Engineering Support

9.2.1 PROJECTS: Rock Mechanics and Reservoir Engineering

LEVEL III OBJECTIVE:

Determine the drive mechanisms for the design well reservoirs by 1991. [G21-01]

Strategy: Production tests at the Pleasant Bayou design well and pressure buildup test at the Gladys McCall design well will continue, and plans for possible tests at a third (Hulin) will be made. For Gladys McCall, checks on the pressure in adjacent geopressured brine zones will be made, and sidetrack cores around the production zones will be taken to find evidence of drive mechanism(s). The reservoir stress state for the design well reservoirs will be modeled using geology, rock compressibility, and reservoir pressure data.

Status: Among the possible drive mechanisms for geopressed reservoirs are:

1) elastic compression of the fluid-rock matrix;
2) irreversible rock compaction;
3) long-term formation creep;
4) cross flow from overlying/underlying sands;
5) shale water recharge;
6) leakage across boundary faults; and
7) gas drive.

Elastic compression of the rock and fluid drives most gas and oil reservoirs that produce with pumping. While this force certainly contributes to the production of geopressed brines, models based on compression alone have been unable to predict the observed long term production of geopressed brines.

Parametric simulations of pressure testing of a geopressed well suggest that irreversible rock compaction is not a major pressure maintenance mechanism.

Shale water recharge, as a pressure maintenance mechanism, seems unlikely because the volume of shale immediately adjacent to the Gladys McCall sandstone reservoir is not large enough to account for pressure maintenance.

Gas drive has been ruled out as well for the Gladys McCall reservoir. A 1987 drawdown test at Gladys McCall, in which the wellhead pressure was substantially decreased, did not detect any free gas in the reservoir.

Cross flow from other sands and leakage across boundary faults seem the most likely pressure maintenance mechanisms. They are consistent with reservoir drawdown data. Pressure testing of adjacent sands at the end of the long-term pressure build-up test in 1989 may determine if cross flow is occurring.
After the scientific testing program at Gladys McCall is completed, the computer simulator will be updated to include the most likely pressure maintenance mechanisms. This should increase the accuracy of predicting long-term well performance on the basis of short-term tests. Future tests of the well at Pleasant Bayou (and the Hulin well, if tested) will serve to corroborate the predictions.

Milestones:

1. Begin flow testing at Pleasant Bayou. (6/88)
2. End long-term pressure build-up test at Gladys McCall. (10/89)
3. Complete final scientific testing program at Gladys McCall and plug and abandon well. (1/90)
4. Complete final scientific testing program at Pleasant Bayou and plug and abandon well. (3/91)

LEVEL III OBJECTIVE:

Develop a test procedure which has sufficient accuracy to predict the capability of any geopressed reservoir to be produced for a period of five times as long as the test period by 1992. [G21-02]

Strategy: Accurate prediction of long-term geopressed production will decrease the risk of developing the resource. When drive mechanisms are ascertained for geopressed reservoirs, these mechanisms, along with appropriate rock mechanics data, will be incorporated into the numerical simulator, thereby enhancing the ability of the simulator to predict long-term geopressed fluid production.

Status: Long-term pressure buildup testing at Gladys McCall will continue until a final scientific testing program is begun. Information from these tests should help determine drive mechanisms. The Pleasant Bayou flow test will continue to provide drawdown data which also may help to determine drive mechanisms. Compaction testing and tensile failure testing of geopressed rocks will supplement the field tests.

Milestones:

1. Began tensile failure testing of geopressed-geothermal sandstone. (10/88)
2. Complete final scientific testing program at Gladys McCall well. (1/90)
3. Complete compaction testing of Gladys McCall cores. (10/89)
4. Complete compaction testing of Pleasant Bayou cores. (10/90)


9.2.2 PROJECT: Logging

LEVEL III OBJECTIVE:

Develop techniques to increase confidence in the ability to locate and evaluate geopressured resources by 1992 such that at least 90 percent of wells recompleted for geopressured-geothermal development are subsequently shown to be economic. [G22-01]

Strategy: Routine geological information (e.g., logs, geophysical surveys, cores, fluid samples) is available for most Gulf Coast wells. That information can be synthesized in such a way that geopressed resources may be identified and evaluated more readily. Well-logging information will be developed which, in conjunction with existing geology and geophysical techniques, permit the location and evaluation of potentially economic geopressed-geothermal resources. The effects of rock stress, shale content, and wettability on rock resistivity will be studied and the effect of trace elements on neutron logs will be determined to improve the interpretation of logs from geopressed wells. The techniques will be combined into a standard procedure that operators can use during or immediately after drilling operations to indicate resource potential.

Status: Enhanced logging techniques increase a developer's ability to evaluate the potential geopressed-geothermal reservoirs in a well. Researchers have shown in prior work that large daily variations in mud resistivity and mud filtrate resistivity occur in many wells during drilling. Uncertainties in mud filtrate resistivity increase the error of several log interpretation procedures. Studies show that reducing the variation in resistivity of mud make-up water should reduce mud filtrate resistivity fluctuations.

DOE is co-sponsoring logging research with Phillips Research Center, Tenneco Oil Exploration & Production, Schlumberger Well Services, ResTech, Exxon Production Research Company, Mobil Research & Development Corporation, Schlumberger-Doll Research, and Sun. This research deals mainly with improving the interpretation of electric and neutron logs.

Researchers currently are studying the effect of shale content, wettability, reservoir rock stress, and fluid pressure on the cementation exponent and the saturation exponent in the Archie Equation. The saturation exponent is often assumed to be 2, in spite of the fact that considerable data, not obtained under reservoir conditions, show that values can range from 1.3 to greater than 3. Researchers will measure several different types of reservoir rock at in situ pressures to correlate rock type with changes in cementation and saturation.

Researchers also are evaluating the effect of 16 trace elements with very high thermal neutron capture cross-sections on the neutron log. These elements can mimic the hydrogen atom in neutron capturing ability, and cause a misinterpretation of neutron logs. Boron, an element found in high concentrations in some Gulf Coast wells, is one of the principal trace elements being evaluated.
Milestones:

1. Complete evaluation of the effect of trace elements on the neutron log. (9/90)
2. Complete resistivity logging research. (9/92)

PROJECT: Liquid Hydrocarbons

LEVEL III OBJECTIVE:

Determine source and flow mechanisms for the liquid hydrocarbons and methane being obtained from producing geopressed reservoirs by 1991. [G23-01]

Strategy: Geopressed brines contain cryocondensates (aromatic hydrocarbons) in small quantities, principally benzene, toluene, and xylene. The gas streams from all the DOE design wells contain these compounds, and archival brine samples from the "wells of opportunity" contain the more soluble lower molecular weight aromatic compounds. Laboratory analyses of hydrocarbon composition will be obtained. The geology of the reservoirs and adjacent oil or gas wells which might be producing from geopressed zones will be studied. Shale cores will be examined as potential source rock.

Status: Monthly sampling at the Gladys McCall well indicated variations in cryocondensate concentrations with time. Aliphatic hydrocarbons (heavy oil) were also produced at Gladys McCall. Researchers currently hypothesize that the oil is released from the shale when the reservoir pressure is reduced enough to cause oil migration from the shale to the sandstone. A low flow rate of 10,000 barrels of brine per day at Gladys McCall in 1987 allowed the reservoir pressure to recover partially, and oil production at the surface facilities ceased. Apparently, the pressure gradient across the sandstone (the producing formation) and shale interface was no longer large enough to allow the oil to migrate.

Coring is proposed in the final scientific testing program for the Gladys McCall well in 1989. If the shale is cored, it will be analyzed to determine whether it is the source rock for the hydrocarbons.

Milestones:

1. Core and analyze confining shales at Gladys McCall reservoir. (1/90)
2. Core and analyze confining shales at Pleasant Bayou reservoir. (3/91)
3. Determine source and flow mechanisms of liquid hydrocarbons. (9/91)
LEVEL III OBJECTIVE:

Determine if fluids can be disposed of in an environmentally acceptable manner by 1995. [G24-01]

Strategy: The chief environmental effects associated with the development of geopressed resources in the Gulf Coast region are land-surface subsidence, growth-fault activation, and water quality changes. Consequently, surface subsidence, induced seismicity, and water quality in aquifers above the injection zones and in surface waters will be monitored both during and after site operations. A model for reservoir compression will evolve which should verify that no adverse environmental effects will occur from the planned production and disposal methods over a ten-year period of operation.

Status: A plan for monitoring impacts was developed before resource testing began and has since been implemented consistently at each of the test well sites.

Regional first-order vertical surveys were used to determine base line rates of subsidence in each prospect before well testing, and to monitor changes in land surface elevation during and after testing. Networks of first-order elevation benchmarks were installed in the immediate vicinity of each test well.

To determine the effects of fluid production and disposal on local growth fault activity, microseismic monitoring arrays were established in the vicinity of each test well. Each network consists of five to seven short-period vertical motion seismometers. The seismic signals are amplified and transmitted via phone lines to the Louisiana Geological Survey for analysis. Microseismic networks are located at the Gladys McCall well, the Pleasant Bayou well, and the Hulin well.

Geopressed brines are high in total dissolved solids, principally sodium, chlorine, and calcium. These and other constituents could contaminate surface and ground water if not handled and disposed of properly. Surface and ground water at the well sites are sampled and analyzed quarterly to detect any possible contamination.

So far, no significant adverse environmental impact related to the well activities has been detected. Environmental monitoring will continue at the test sites until about two years after the completion of flow testing.

In conjunction with the University of Texas at Austin, the Louisiana Geological Survey will develop a subsidence model for geopressed reservoirs beginning in FY 1990.

Milestones:

1. Begin development of subsidence model. (10/89)
2. End development of subsidence model. (9/91)

3. Complete environmental monitoring at geopressed well sites (two years after cessation of flow testing).

9.3 TASK: Energy Conversion

9.3.1 PROJECT: Pleasant Bayou Hybrid Power System

LEVEL III OBJECTIVE:

Develop hybrid conversion technology with thermal efficiency at least 20% greater than that from separate combustion and geothermal power cycles by 1992. [G31-01]

Strategy: The strategy is to establish hybrid technology for using the heat, methane, and hydraulic pressure of geopressed brines. The heat and methane can be used to generate electricity, or the heat can be used separately for direct application, or electric power production and the methane sold to a pipeline. Cost-shared utilization experiments will help to establish the technical feasibility of efficient power conversion methods. They will provide a basis for industry to compare the advantages of electric power production versus straight sales of gas.

Status: DOE and EPRI are co-sponsoring a hybrid, 1-MWe power system at the Pleasant Bayou site in Brazoria County, Texas. Equipment from the DOE Geothermal Test Facility in the Imperial Valley of California has been refurbished by EPRI and delivered to the Pleasant Bayou site. Construction of the hybrid power system will be completed in April 1989, and the system will be operated for about one year. The first three months of operation will be a shakedown period; the remaining nine months will be for continuous operation. The DOE/EPRI hybrid power system will be the first geopressed-geothermal installation to generate electricity.

Milestones:

1. Began construction of hybrid power system. (1/89)
2. Begin operation of hybrid power system. (4/89)
3. Complete operation of hybrid power system. (4/90)
10.0 HOT DRY ROCK RESEARCH CATEGORY

10.1 TASK: Fenton Hill Operations

10.1.1 PROJECT: Phase II Energy Extraction System

LEVEL III OBJECTIVE:

Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics by 1993. [D11-01]

Strategy: GTD will conduct short-duration and long-duration (one year) flow tests of the Phase II reservoir at Fenton Hill. During the period of thermal drawdown, the important parameters of reservoir behavior, geochemical interactions, and fluid loss will be measured. Testing and modeling techniques to determine the effective energy production and longevity of fractured HDR reservoirs will be developed.

Status: A long-duration flow test was conducted on the shallow, cooler, Phase I reservoir in 1979. In December 1983, a massive hydraulic fracturing operation created the man-made reservoir to be used as part of the HDR system. With the successful sidetracking operation in 1985 the flow loop was completed and available for open loop testing. Since the completion of the Phase II reservoir two short-duration flow tests have been conducted, a 7-day and 30-day test. Based in part on the results of those tests, a test plan is being developed for a long-duration flow test. Both Phase II tests were conducted open-loop, but the long-duration test will be closed-loop, i.e. after extracting the energy, the produced fluid will be reinjected. The surface equipment for the test is being procured and installed.

Milestones:

1. Ordered surface loop equipment except for the pumps and separator. (9/88)
2. Complete the installation of the surface loop except for the pumps and separator. (9/89)
3. Receive pumps and separator. (4/90)
4. Initiate Long Term Flow Test. (9/90)
5. Prepare a preliminary estimate of the drawdown characteristics of the man-made HDR reservoir at Fenton Hill. (9/91)
10.1.2 PROJECT: Phase II Ancillary Activities

LEVEL III OBJECTIVE:

Verify that the environmental consequences of HDR development are acceptable by 1997. [D12-01]

Strategy: This objective consists primarily of surface and downhole seismic monitoring during and immediately following any downhole pressure/flow operations, plus sampling and chemical/biotic analysis of site water supplies. Monitoring provides environmental surveillance and documentation as required to (1) satisfy state and federal environmental regulations, and (2) establish an environmental baseline which may be used to assess environmental effects. Seismicity at Fenton Hill and vicinity will be monitored continuously to determine any undesirable response from long-term operations. Careful surveillance of surface and ground waters will continue during and after operations at Fenton Hill.

Status: The environment at Fenton Hill has been monitored for over ten years. Geochemical analyses have been conducted on the fluids used for the Fenton Hill experiments. This has been especially important during the short- and long-duration flow tests. In addition, samples from the area’s springs, streams, lakes, and waterwells have been analyzed since 1975. Water from the on-site well is analyzed for organics on a monthly basis and a full chemical analysis is conducted annually. Seismic monitoring is conducted during injection and production experiments to detect any abnormal seismicity in the surrounding area. Furthermore, microseismic event monitoring is used to determine the presence of thermal stress cracking and the extent of the active reservoir. Also, occasional noise level and illumination measurements are made during various types of site operations.

Milestones:

1. Periodically sample and analyze water used for the LTFT. (9/92)

2. Analyze events continuously to help determine environmental impact and the extent of thermal stress cracking. (9/93)

3. Evaluate the environmental consequences of HDR development and determine its acceptability. (9/97)
10.2 TASK: **Scientific & Engineering Support**

10.2.1 PROJECT: **Tools & Instrumentation**

**LEVEL III OBJECTIVE:**

Improve instrumentation and hardware to control, locate, and measure fracture propagation in hot dry rock reservoirs by 1995. [D21-01]

**Strategy:** Variable-pressure flow tests of the Phase II reservoir at Fenton Hill will help to detect fracture propagation and fluid entry and exit locations in the wellbores. Acoustic techniques, particularly the study of microseismic events, are the best means by which direct information can be obtained about reservoir changes away from the borehole. Improved seismic systems will be tested for their fracture measuring abilities.

**Status:** Work will continue to gain as much information as possible from the seismic data obtained during the massive hydraulic fracturing experiment conducted in 1983. Instrument requirements will be developed for measuring and locating seismic events using a single wellbore (injection well) during the fracturing operation and maybe a second wellbore (production well) which would be only partially completed. In order to accomplish this, new instruments, data evaluation systems/techniques, and software may need to be developed. Using the results of the Long-Term Flow Test (LTFT) and the analysis of hydraulic fracturing activities, specifications will be created for the above, and prototype hardware bench tested.

**Milestones:**

1. Review the British and French tool designs. (8/89)
2. Develop a preliminary tool design. (6/93)
3. Conduct shaker testing and final tool design. (6/94)
4. Develop and test prototype instrumentation and hardware to locate and measure fracture propagation in a man-made HDR reservoir. (9/95)

**LEVEL III OBJECTIVE:**

Establish reservoir-mapping techniques to locate drilling targets for production wells by 1995. [D21-02]

**Strategy:** A single-well, seismic measurement technique, such as the hodogram method, will be developed for minimizing the number of observation points required to locate and characterize the man-made reservoir. A technique of this type is required for commercial systems to complete the drilling of the production well and design the completion for the injection well.
Status: Spectral analyses and fault plane solutions for seismic events generated during previous experiments have been carried out. The seismic data acquisition and analysis system will be improved. The results will be verified using data developed during the LTFT, such as gamma logs, temperature surveys, spinner surveys, caliper logs, televiewer surveys, geologic data, wellbore cuttings, geochemical analysis, and other relevant data. Discrete fracture planes will be identified by application of the recently developed "3-point" method. The approach will increase the chance of success of any given system and reduce the cost of drilling wells by minimizing the need for additional wells.

Milestones:

1. Completed preliminary spectral analysis for the previously recorded MHF data. (8/88)

2. Enhance the fault plane analysis for the MHF. (9/89)

3. Integrate the numerical modeling of the shear plane with the spectral modeling above. (7/91)

4. Complete development of methods, techniques and prototype hardware. (9/95)

10.2.2 PROJECT: Reservoir Engineering

LEVEL III OBJECTIVE:

Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers by 1994. [D22-01]

Strategy: Experiments will be conducted to assess the amount of energy remaining in the reservoir. Careful monitoring of the changes in the chemical makeup of the extracted fluids is expected to contribute to the development of analytical models used to estimate the reservoir size and life. In parallel, reacting tracers will be injected into the system to validate the empirical models.

Status: During the Phase I energy extraction experiment, several techniques were used to estimate the size and lifetime of the reservoir. One of the most promising was chemically reacting tracers. Since then a great deal of laboratory work has enhanced their capability. Tracers were used during the 30-day, open-loop, circulation test. The test helped to further the development of implementation techniques and to verify the tracer models enhanced to estimate the thermal lifetime of the reservoir. The fluid has been filtered to reduce the number and concentration of its constituents. Laboratory measurement techniques have been identified for very low concentrations of tracer species — parts per billion. Because of the expected dilution of the fluid, detecting these levels of concentration will be necessary for effective analysis.
Milestones:

1. Filtered one million gallons of water stored in the pond at Fenton Hill. (9/88)

2. Complete the development of techniques for measuring very low concentrations of tracer species -- parts per billion. (8/89)

3. Conduct a reservoir huff-puff experiment using an organic tracer to determine its adsorption. (9/89)

4. Conduct laboratory adsorption studies to characterize the tracers so that later field applications can be accurately interpreted. (6/91)

5. Identify and test chemical tracers and monitoring techniques to establish the volume and temperature of a HDR reservoir. (9/94)

LEVEL III OBJECTIVE:

Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system by 1995. [D22-02]

Strategy: This objective represents the scientific core of the program in which: (a) thermal/fluid dynamic modeling of the reservoir is formulated, verified, and modified as necessary; (b) downhole experiments are planned and directed; (c) acquired data are analyzed in depth; and (d) reservoir configuration is modeled and verified. Included are laboratory and analytical support which will provide measurements of thermophysical and structural properties for use in complex computer modeling. The models will be improved to best represent the performance of the system. This objective also provides theoretical and analytical data support to the Fenton Hill site experiments and to downhole instrument/equipment development. A comprehensive analysis of the LTFT will be completed, including detailed reservoir analyses to verify the hydraulic and thermal models developed to represent the HDR system.

Status: Since the Hot Dry Rock concept was developed in 1970, many models have been created to predict the behavior of the man-made system. As our experiments have become more complex, our understanding of the processes has increased, we have refined our models to better represent the physical phenomena involved. Reservoir characteristics that have been the focus of attention include: heat content, lifetime, flow geometry, impedance, water loss, hydrochemistry, and mineral dissolution/opposition. Our analysis to date has been sufficient to verify the HDR concept but not sufficient to reduce the technical and economic risk of a commercial system. As the models evolve they will be used as design bases for commercial systems.

Milestones:

1. Introduced anisotropy into existing finite element fluid flow and heat transfer models. (9/88)
2. Expand the capability of the preferred model to three dimensions. (9/89)
3. Introduce discrete fractures into the preferred model. (6/93)
4. Verify hydraulic and thermal performance of the Phase II system. (9/95)

LEVEL III OBJECTIVE:

Determine means to locate accurately the intersection of fractures with the wellbore by 1997. [D22-03]

Strategy: GTD researchers will improve the analysis of high-temperature acoustic televiewer data. This should enable the mapping of any irregularities or discontinuities in the wellbore. Also, the automation of the 3 point method, a technique for locating fracture planes in the man-made reservoir, will be improved. Subsequently, a technique for identifying the orientation of the strike and dip of fractures in the native rock and estimating the tectonic stress should be feasible.

Status: A prototype high-temperature televiewer has been built and field tested. The resulting data have been reduced in the laboratory to help identify the geological structures. Fractures have been identified in the openhole section of an HDR well and confirmed using data from other sources. The advancement of acoustic techniques, particularly the study of microseismic events, has provided a significant method by which information about changes in the reservoir can be obtained from locations away from the boreholes. Using the three point method, we have postulated the existence of planar structures within the reservoir and used that information to help select targets for the EE-2A redrilling campaign. Analytical techniques have been identified that may assist in estimating the orientation of the strike and dip of the native rock and its tectonic stress.

Milestones:

1. Study the feasibility of predicting the arrival of the compression and shear waves. (9/89)
2. Complete the automation and further enhancements of the 3-point method. (6/92)
3. Develop a technique for identifying the orientation of the strike and dip of the native rock and estimate the tectonic stress. (6/95)
4. Develop and verify techniques for accurately locating the intersection of fractures with the wellbore. (9/97)

LEVEL III OBJECTIVE:

Complete studies on water-rock interactions and their effects on flow through a hot dry rock reservoir by 1993. [D22-04]
**Strategy:** Flow tests of the Phase II reservoir will be conducted for both short and long periods of time. Geochemical measurements of the circulating fluid will be made during these tests to detect changes. An assessment will be made of the potential impact on the system from scale/corrosion/erosion. If appropriate, procedures will be developed to protect the surface system and the reservoir.

**Status:** HDR reservoir fluids have been monitored since the first experiments in the Phase I loop at Fenton Hill. The constituents of the fluids have been used to determine reservoir contaminants, estimate the ambient temperature of the reservoir, estimate the reservoir's lifetime and evaluate the reservoir's geology. Models have been constructed to fit the available data. Ongoing studies of the geochemistry at Fenton Hill provide assurance that the technology is environmentally acceptable. These studies also allow detailed reservoir analyses and modeling of hydraulic and thermal performance, aid in determining fracture locations, and provide information on water-rock interactions and their effects on flow through the reservoir.

**Milestones:**

1. Assemble geochemistry trailer and associated equipment at Fenton Hill in anticipation of the LTFT. (3/90)

2. Complete the first of three fresh water flushes of the reservoir to monitor the rate at which the fluid reaches equilibrium. (12/92)

3. Prepare a preliminary assessment of the water-rock interactions of a power production system. (9/93)

### 10.2.3 PROJECT: Technology Applications

**LEVEL III OBJECTIVE:**

Determine if the performance of the Fenton Hill Phase II reservoir, when considered as a unit reservoir in a commercial-scale project, could support production of electricity at an economical busbar cost by 1995. [D23-01]

**Strategy:** Results from the flow tests will be combined with data on the cost of wells and cost/performance of binary power plants to estimate overall cost of power from commercial-scale projects.

**Status:** A preliminary economic assessment of electric generation applications has been conducted by EPRI from the utility viewpoint. In addition, several HDR economic studies have been performed by other organizations (i.e., the Los Alamos National Laboratory; Bechtel National, Inc.; and the United Kingdom Department of Energy). The planning for a comprehensive systems study will begin in FY 1991. The critical input into this study will be the technical evaluation of the LTFT, which will be conducted under other objectives. Other important inputs will be the results of the HDR experiments conducted by other countries, i.e., Japan, United Kingdom, USSR, Sweden, France, and West Germany.

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An important outcome of this objective is the transfer of the system engineering and resource information, as well as hardware developments, from the HDR program to the geothermal industry. Reciprocally, such exchange affords access to current industrial technology for application to HDR technology.

Milestones:

1. Complete a comprehensive systems study after the results of the LTFT are evaluated and published. (9/96)
11.0 MAGMA RESEARCH CATEGORY

11.1 TASK: Long Valley Operations

11.1.1 PROJECT: Drilling and Engineering

**LEVEL III OBJECTIVE:**

Confirm the existence of a shallow magma body with the drilling of an exploratory well by 1992. [M11-01]

**Strategy:** An exploration well is the only sure means to confirm the existence of a magma body. A borehole will be drilled in recent volcanic terrain where geologic and geophysical evidence suggest the presence of a shallow magma body. Observations from the well should enable precise measurements of the body's size, shape, and location. The well should also enable the testing of first generation drilling techniques and materials required to enter into a magma body.

**Status:** An independent DOE review panel finalized the location of the Long Valley, California, drill site in January 1988. Since that time, a drilling permit has been issued by Bureau of Land Management (BLM). Well design specifications have been completed for all four drilling phases. Casing has been purchased for Phase I drilling which is scheduled in the summer of 1989. Requests for Quotations (RFQ's) have been solicited from candidate drilling contractors. And initial site preparation activities, such as removing the earlier conductor pipe, have been undertaken.

**Milestones:**

1. Select drilling contractor for initial drilling. (3/89)
2. Phase I drilling to 2,500 feet. (7/89)
3. Phase II drilling (deepen to 7,500 feet). (7/90)
4. Phase III drilling (deepen to 14,000 feet). (7/91)
5. Phase IV drilling (deepen to 20,000 feet). (7/92)

11.1.2 PROJECT: Supporting Science

**LEVEL III OBJECTIVE:**

Understand the nature of geophysical anomalies at the Long Valley caldera using well observation data by 1992. [M12-01]

**Strategy:** The strategy is to seek further understanding of the geophysical anomalies at the Long Valley caldera by drilling a deep exploratory well in stages. An interim period between stages will facilitate in situ experiments
and data collection. Downhole measurements will avoid the attenuation and structural complications introduced by caldera fill and provide better quality data to verify the geophysical anomalies.

**Status:** Geophysical methods have proven successful in identifying likely magma targets. In fact, it was through these methods that a current magma drill site was selected. Twenty-one potential sites were evaluated in terms of suitability for conducting a long-term energy extraction experiment. Long Valley ultimately was selected as the primary site based on the extensive geophysical, geological, and geochemical studies completed in the area. However, the many studies have not resulted in any conclusive evidence regarding the best site to drill in the caldera. Geodetic and other data show anomalies in the basement beneath the resurgent dome and beneath Mammoth Mountain. In addition, some data support a possible magma source in the western portion of the caldera based largely on a high-temperature hydrothermal system.

Until a magma exploratory well is drilled, there is no way to determine the nature of identified geophysical anomalies at Long Valley caldera. The well, planned in the south-central portion of the caldera, will allow downhole measurements without the attenuation and structural complications introduced by caldera fill. Once the well is beyond a depth of 7,000 feet, geophysical measurements will be made. Results from these measurements will be correlated with the abundant surface data available on the caldera. A Magma Science Committee has been established to coordinate the scientific experiments in the well. Other groups, besides GTD, participating in scientific aspects of the Long Valley operations include: National Science Foundation, United States Geological Survey, and Office of Basic Energy Science (DOE). Plans for the supporting science activities are being formulated.

**Milestones:**

1. Developed draft science guide for Long Valley well (Phase 1). (9/88)
2. Finalized management plan for outside research participants. (2/89)
3. Completed final science guide for Long Valley well. (3/89)
4. Select individuals for specialized research panels. (4/89)
5. Instrument Long Valley well to study geophysics. (10/90)
11.2 TASK: Laboratory & Engineering Support

11.2.1 PROJECT: Drilling Techniques

LEVEL III OBJECTIVE:

Design and develop technology capable of drilling into molten magma at temperatures of at least 900°C and total depths of at least 5 km by 1992. [M21-01]

Strategy: For a prospective magma extraction process to succeed, there must be drilling technology and materials available to withstand the higher temperatures, pressures, and volumes of dissolved gases expected in a magma environment. GTD researchers will design, fabricate, and test drilling equipment and/or materials for penetrating a magma body. Research will be conducted on a number of problems. The first is creep of viscous rock that could cause the wellbore to squeeze in behind the bit during drilling. The second involves reheating of the surrounding rock and creep closure of the well after circulation is lost.

Status: Conceptually, deep crustal magma bodies can be drilled with the same technology used to core the Kilauea Iki lava lake. That technology consisted of specially designed core barrels and water-cooled diamond coring bits. The bits used forward-facing, high-velocity pressure jets to penetrate and cool magma ahead of the bit. Before this technology can be considered at the Long Valley site, two differences must be considered: an overlying high-temperature hydrothermal system, and the impact of the higher in situ pressures and dissolved gases.

Research in Hard Rock Penetration (Section 8.2.1) is addressing the problem of extreme heat by examining the use of an insulated drill string to control drilling fluid temperatures. Drilling fluid temperature affects the performance of additives and the strength and corrosion rate of tubulars, bit life, and borehole stability. For these reasons, the design of insulated drill string has become a crucial need for magma research.

Equally important is research on general wellbore stability—the problems of creep of the surrounding hot rock and reheating of the surrounding rock after circulation is lost. To address these concerns, research is planned on high-temperature weighting materials for the drilling fluid and materials for casing support.

Milestones:

1. Specify materials and equipment needs for the Long Valley well. (9/90)
2. Identify final material and equipment needs to drill into a prospective magma body. (9/91)
3. Plan the procurement of materials and equipment for energy extraction activities. (3/92)
11.2.2 PROJECT: Energy Extraction

LEVEL III OBJECTIVE:

Evaluate heat transfer effectiveness between a magma body and water circulating in the energy extraction wellbore. [M22-01]

Strategy: The strategy seeks to evaluate heat transfer effectiveness using laboratory experiments of fluid/magma interaction. Laboratory experiments with analog magmas will be conducted. Thermal fracturing experiments will be performed using results from simulated magma solidification.

Status: A number of bench-scale magma energy extraction experiments have been completed. For example, experiments were carried out using a low-temperature simulant (plastic) to show that a magma-like material when solidified will produce a three-dimensional network of interconnected fractures. Also, a series of magma convection experiments - using simulant material (corn syrup) with a viscosity of rhyolitic magma - were conducted to provide additional insight for modeling the impact of magmatic convection. Research results from these experiments are producing needed guidelines for projecting energy extraction calculations from a magma body. Additional experiments in this area are planned.

Ongoing research is directed at developing a fundamental understanding of an open, direct-contact heat exchanger in a crustal magma body. The energy extraction rate has a direct influence on the economic viability of the magma extraction concept. An open heat exchanger, in which fluid is circulated through the interconnecting fissures and fractures in the solidified region around the well, offers the promise of very high rates of heat transfer.

To evaluate heat transfer processes, experiments have been designed to address five areas: 1) fundamental mechanisms of solidifying and thermally fracturing magma; 2) convective heat transfer in the internally fractured solidified magma; 3) convective flow in the molten magma and heat transfer from the magma to the cooled heat exchanger protruding into it; 4) numerical simulation of the overall energy extraction process; and 5) the thermodynamics of energy conversion in a magma power plant at the surface.

Milestones:

1. Determine magma solidification patterns for primary and secondary fractures. (10/90*)
2. Develop detailed models of magma heat transfer patterns. (12/91*)
3. Determine impact of magma and water interactions. (12/91*)

*Tentative
11.2.3 PROJECT: Geochemistry & Materials

LEVEL III OBJECTIVE:


Strategy: The strategy seeks to evaluate the performance of materials, including high-temperature casing support and weighting materials. Areas that will be addressed include: characterization of available commercial metals that are compatible with a rhyolitic magma environment. The work supports ongoing activities under Drilling Techniques (Section 11.2.1).

Status: Seventeen commercially available alloys have been evaluated for compatibility with magma. Based on research results to date, the corrosion problem for most alloys tends to be oxidation. These findings are based on extensive testing of metals using simulated magma believed to have mineral compositions and volatile concentrations of crustal bodies in the Long Valley caldera area. The test metal specimen is sealed with volatile-bearing rhyolite glass in a gold tube. The tube is then subjected to the desired pressure and temperature conditions to study selected parameters. Research is being pursued on nickel-based materials which have proven to be the most promising alloys; of particular interest are reaction rates between alloys and silicates.

Milestones: (Included under Objective M21-01)

Predict rates for dissolution of silicate minerals and the composition of fluid in rock-to-water heat exchanger system, and evaluate the potential for loss of permeability due to precipitation of secondary minerals by 1995. [M23-02]

Strategy: The strategy is to understand dissolution/transport kinetics by two means: 1) predicting silicate dissolution rates and solution composition in a direct contact heat exchanger; and 2) evaluating the potential for loss of permeability due to precipitation of secondary minerals. Magma convection will be simulated in laboratory experiments. The physical processes involved in heat transfer from magma bodies will be studied and appropriate mathematical models developed.

Status: An experimental facility has been built to study leaching and precipitation of minerals, specifically feldspars and quartz. These two minerals are expected to be prevalent in a magmatic system. Current research focuses on (1) determining the importance of several variables, such as pH, solution composition, and mineral defects on feldspar dissolution in aqueous solutions, and (2) measuring quartz dissolution as a function of temperature, pressure, and orientation using a rotating disc autoclave.
Milestones:

1. Determine quartz and feldspar dissolution mechanisms. (12/91)

2. Determine the impact of rock-water interactions on fractured media. (12/91)

LEVEL III OBJECTIVE:

Evaluate magma degassing hazards associated with drilling and energy extraction at Long Valley, California. [M23-03]

Strategy: Since drilling into a magma chamber has never been done, it is critical from a safety viewpoint to understand the hazards of a volatile-rich rhyolitic magma chamber. Therefore, the strategy attempts to look at the degassing hazards of penetrating a magma chamber which is believed to contain silicate-rich minerals and free gases, particularly pressurized water vapor. The geochemistry of magmas (with emphasis on fluid inclusions) will be characterized in order to understand compositional variations and phase relationships.

Status: To help evaluate any potential hazards, studies have been undertaken to characterize the Long Valley magma. Using the results of the characterization study, researchers are trying to understand the dynamics of an erupting magma body by studying flow and cooling patterns in simulated magma. Ongoing research is attempting to answer questions such as: 1) will the magma cool fast enough to seal off the penetrated area, or 2) will it work its way toward the surface and possibly cause an eruption as the escaping gases are released?

Milestones:

1. Identify most likely safety hazards and address impact on the program. (12/90)

2. Develop plan for handling any prospective safety hazard. (12/91)