MASTER

FINAL REPORT

**Geothermal Exploration and
Assessment Technology
Program Plan**

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Department of Geology and Geophysics

**University of Utah
Salt Lake City, Utah (USA)**

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**Prepared for
DEPARTMENT OF ENERGY
Division of Geothermal Energy**

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GEOTHERMAL
EXPLORATION AND ASSESSMENT TECHNOLOGY
PROGRAM PLAN

Salt Lake City, Utah

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1.0 Introduction

This document describes a plan for the Department of Energy (DOE) Program in Geothermal Exploration and Assessment Technology. The purpose of this Program is to provide assistance to the Nation's industrial community by helping to remove technical and associated economic barriers which presently inhibit efforts to bring geothermal electric power production and direct heat applications on line. Federal involvement in providing such assistance is detailed in Public Law 93-410, the Geothermal Energy Research, Development, and Demonstration Act of 1974, and in ERDA-86, the Definition Report for the Geothermal Energy Research, Development and Demonstration Program, published by ERDA in October, 1975, in response to P.L. 93-410.

The Program in Geothermal Exploration and Assessment Technology is an industry-driven program. The *present* plan is based on a substantial review, conducted in concert with industry, the USGS, and academia, of the technical and associated economic barriers to *commercial hydrothermal* development which currently face industry (Ward, 1978; Goldstein, Norris and Wilt, 1978). Continued input from the industrial community through several standing Technical Review Committees and an Industrial Review Panel will ensure meaningful program input, review, and update and will ensure consideration of exploration and assessment problems associated with development of low- to high-temperature convective hydrothermal resources and of geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient resources, if required. Current emphasis is on high-temperature convective hydrothermal resources. In addition, this Program Plan is, and

will continue to be, responsive to needs recognized in each of the three Regions recently established by the Division of Geothermal Energy (DGE) of the Department of Energy:

- the Pacific Region
- the Rocky Mountain/Basin and Range Region
- the Eastern Region

Problems as recognized today whose solutions are or will be important in the near-term (1985), mid-term (2000), and far-term (2020), are addressed by this Program Plan. Near-term problems, and strategies to solve those problems, are generally more closely defined than are mid- or far-term problems. Near-term work encompassed by this Program Plan deals mainly with development of new technology for exploration and assessment within known areas of surficially-expressed high-temperature *convective hydrothermal* systems, whereas mid- and far-term work deals mainly with development of technology to discover new resources which usually lack significant surface manifestation and whose discovery is vital to the Nation's mid- and far-term energy needs. Part of this Program Plan deals with continued elucidation of exploration and assessment problems over the next few years so that effective methods will be available for all stages in the maturity of the national geothermal program.

The Geothermal Exploration and Assessment Technology Program is intended to be comprehensive in that it is prepared to address exploration and assessment technology development for each of the six types of geothermal resources currently recognized, namely:

- Convective Hydrothermal
- Geopressured
- Hot Dry Rock
- Magma
- Radiogenic
- Normal Geothermal Gradient

The scope of this Program includes development of technology and interpretation methods for geoscience observations conducted:

- At or above the earth's surface
- Between the surface and sub-surface in boreholes
- Between boreholes
- On drill cuttings and core
- On geothermal brine and groundwater.

The Geothermal Exploration and Assessment Technology Program complements the following DOE/DGE research programs dealing with other aspects of geothermal development:

- Reservoir Engineering
- Well Log Interpretation
- Well Log Instrumentation
- Drilling and Completions
- Subsidence
- Induced Seismicity

In addition this Program is closely related to the U.S. Geological Survey's

Geothermal Research Program that has objectives dealing with characterizations of various kinds of geothermal systems, regional and national assessments of geothermal resources, and evaluation and development of scientific concepts for identifying and describing these resources. A careful coordination with all of these programs will be maintained to ensure that no undesirable overlap occurs.

Benefit/cost studies have been made for the elements in this Program Plan and are discussed in detail below. These studies indicate that as much as 50% of the total \$20 million needed to prove the existence of a 200 MWe convective hydrothermal reservoir could be saved through improvement in exploration and assessment technology. Considered in light of the more than 200 high-temperature hydrothermal systems that are expected to be explored by industry in the United States by the year 2000, the accrued benefits will be approximately 40 times the estimated program costs (Dhillon, et al., 1978). This program will also provide significant benefits to exploration for and assessment of moderate and low-temperature hydrothermal systems as well as to the other resource types.

2.0 Barriers to Commercialization of Geothermal Energy

Technical, economic and institutional barriers strongly inhibit commercialization of geothermal energy in the United States. This fact was formally recognized by the Congress with the passage of Public Law 93-410. P.L. 93-410 and ERDA-86 both list goals and objectives (see 4.0 and 5.0) to be accomplished in order to assist industry to develop geothermal energy. That industry needs this assistance is amply demonstrated in such documents as Ward (1978). Although these goals and objectives are specific in nature and comprehensive in scope, they do not constitute a work plan. Therefore, the work to be performed under this Program has been and will continue to be determined through review and distillation, in the context of P.L. 93-410 and ERDA-86, of input collected from industry, government and academic professionals as discussed in detail below.

The basic goal of the Geothermal Exploration and Assessment Technology Program is to aid the Nation's industrial community through identification and removal of technical and associated economic barriers to timely commercialization of geothermal energy. [See section 4.0 for a detailed discussion of goals.] At the present time, development of the Nation's geothermal resources is seriously lagging because use of these resources is not always economically profitable. Improvements in exploration and assessment technology could substantially lower costs for industry to bring electrical power and direct heat on line.

Because geothermal resources of the convective hydrothermal type are likely to be exploited first, due to industry's current economic interest only in these kinds of resources, development of technology to improve

exploration and assessment for convective hydrothermal resources is highest in priority. In order to identify initially the technical and associated economic barriers most critical to industry's development of hydrothermal resources, eight technical review committees of specific expertise were assembled by the University of Utah early in FY78. These committees were composed of a total of about 50 geothermal scientists from the industrial, governmental and academic communities. They were charged with the specific responsibility of developing recommendations for the research most urgently needed in their individual fields. These recommendations for critical research were presented for comment to a review panel formed mainly of geothermal program managers from industry. The sum total of this estimated 750 professional hours of external program input (Ward, 1978) was distilled by the developers of this Program Plan into the list of critical barriers given in Table 2-1. Individual discussion of these barriers is given in Appendix 1.

The present Program Plan addresses most heavily strategies which, when pursued, will lead to removal or reduction of the barriers to hydrothermal commercialization listed in Table 2-1. In addition, a portion of the Plan indicates activities which will lead to identification of exploration and assessment technological barriers to the commercialization of the remaining geothermal resource types, namely: *geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient*. Future updates of this program plan will contain these latter barriers and end-result program objectives to remove them.

TABLE 2-1

BARRIERS TO HYDROTHERMAL COMMERCIALIZATION

- Drill-site selection techniques for assessment, confirmation and production drilling are poor so that far too many "dry" holes are drilled.
- Reservoir delineation (in terms of reservoir limits, depth, temperature distribution, and quantity and properties of contained fluid) by surface geoscience observations and shallow drilling methods is uncertain.
- Conceptual and working models of reservoirs are unreliable. Better models would facilitate more accurate prediction of expected surface and subsurface response to geoscience measurement and mapping techniques, enabling improvements in those techniques.
- Discovery costs for new reservoirs are excessive and methods are of uncertain reliability. It is estimated that discovery costs can be reduced by 50%.
- The lag in transfer of technology to industry from the national laboratories, universities, private foundations, and private contractors must be reduced if more cost-effective exploration and assessment are to be effected at the earliest date.

3.0 Benefit/Cost Analysis for Exploration and Assessment Technology (Hydrothermal Systems)

Exploration and assessment technology plays a major role in the first phase of a high-temperature hydrothermal development project, namely, in efforts to discover and then prove the existence of a reservoir of potentially commercial size, temperature and productivity. Typically, this first phase requires risk capital of about 10 per cent of the total development cost (Ward, 1978, Sec. 6). This initial, high-risk investment should be amenable to significant reduction in three important areas:

1. more efficient well siting, resulting in fewer dry wells, and in completions in the best producing formations,
2. improved reservoir performance predictions from surface, surface-to-borehole and borehole-to-borehole geoscience measurements, and
3. reduced drilling costs.

This section addresses the first item and portions of the second item, since programs for the reduction of drilling and completion costs (Newsom, et al., 1978) and for geothermal reservoir engineering technology development (Anon., 1977) have already been established.

Appendix 3 gives details of a quantitative estimate of the reductions in required risk capital deemed possible through appropriate technology development. Exploration, assessment, and confirmation costs can be reduced by achieving 1) improved geoscience tools and techniques, 2) optimized strategies for applying these tools and techniques, and 3) better reservoir models. Cost savings would result from: 1) lower exploration,

assessment and confirmation costs, and 2) fewer dry holes, and therefore less total drilling.

It is estimated in Appendix 3 that exploration costs exclusive of drilling eventually could be cut in half and that the success ratio¹ for drilling easily could be increased from a present 21 per cent to somewhere between 26 and 36 per cent. The total cost savings, including drilling, would amount to an estimated 30 to 50 per cent of the total \$20 million needed to prove the existence of a field. Such a savings assumes great importance in overall economic analysis of the field, because of the time value of money for such front-end costs. The benefit/cost ratio for this program is estimated to be 20 to 50.

¹ Success ratio = number of successful holes/total number of holes, where a successful hole is an exploration, assessment, or confirmation hole which intercepts potentially commercial quantities of hydrothermal fluid.

4.0 Goals

The basic goal of the DOE Geothermal Exploration and Assessment Technology Program is to aid the Nation's industrial community through identification and removal of those technical and associated economic barriers to commercialization of geothermal energy which arise in inadequate or inferior geoscientific exploration and assessment methods and strategies. A secondary goal is to identify longer lead-time basic and applied research which will foster commercialization of geothermal energy in the mid- and far-term.

The above two goals are DOE's response to certain goals for the national geothermal program for Resource Inventory and Assessment and for Research and Development which are given in Public Law 93-410 in Secs. 103 and 104, respectively. These specific national program goals include:

- "Improvement of geophysical, geochemical, geological, and hydrological techniques necessary for locating and evaluating geothermal resources." *
- "Development of better methods for predicting the power potential and longevity of geothermal reservoirs." *
- "Determination and assessment of the nature and power potential of the deeper unexplored parts of high temperature geothermal convection systems." *
- "Survey and assessment of regional and national geothermal resources of all types."
- "Research to develop, improve, and test technologies for the discovery and evaluation of all forms of geothermal resources...", *
- "...research into the principles controlling the location, occurrences, size, temperature, energy content, producibility, and economic lifetimes of geothermal reservoirs."
- "Research and development...for the purpose of resolving all major

technical problems inhibiting the fullest possible commercial utilization of geothermal resources in the United States." *

- Provision "for an adequate supply of scientists to perform required geothermal research and development activities."

In reply to this Congressional mandate, ERDA issued ERDA-86, the Definition Report for the Geothermal Energy Research, Development, and Demonstration Program. This document broadly defines a DOE program to be undertaken in order to achieve certain goals stated in P.L. 93-410.

The goals listed in P.L. 93-410 and the activities listed in ERDA-86 are general in nature. They allow ample scope, and at the same time provide authority for this program to address itself to industry-determined end-result objectives which, when achieved, will remove the pertinent geoscientific technical and associated economic barriers which face industry.

* Goal for which DOE/DGE plays the major role.

5.0 Objectives

The original objectives, according to ERDA-86, still hold true today, i.e. "Efforts in this area are aimed at reducing the risks associated with exploration and the unknowns associated with the location and extent of geothermal resources. Included are: geosciences research to improve the fundamental understanding of the geothermal processes in the earth's crust and their associated surface manifestations; *exploration and assessment technology development to improve the efficiency, reliability and economics of exploration and assessment*; regional and national assessment to identify and quantify the Nation's geothermal resources; and, resource information dissemination for processing and effective distribution of data on the Nation's geothermal resources." The italicized section represents a primary DOE/DGE responsibility.

ERDA-86 scopes the above objectives in terms of activities in the following fashion:

"The federal program to improve the assessment and exploration technology includes the following activities:

- a detailed definition of the present capabilities and limitations to gather data, to analyze data and to predict geothermal resources.
- an evaluation of the state of knowledge of individual geothermal sites or reservoirs.
- an analysis of the potential for improving the major techniques, technology, and/or instrumentation.
- planning of efficient use of multiple instruments and

- data analysis techniques in a systematic sequence to converge reliably on selection of a drilling target.
- studies of new and/or improved analytical techniques.
 - a determination of geological, geophysical, geochemical, and hydrological parameters and circumstances (such as detailed descriptions of formations) of geothermal resources and their relationships to location.
 - efforts to improve or devise new advanced exploration instruments and supporting equipment.
 - field work to evaluate the new exploration techniques and improved hardware, software, analytical techniques, and methods of interpretation including verification of results with information from deep wells and their logs."

The above objectives and activities are conveyed into a program logic flow chart in Figure 5-1. The first assumption, verified by several years of exploration experience, is that identifiable and serious deficiencies exist which impact on one or more of the phases of geothermal resource development and exploitation. Regardless of the resource type, these phases normally commence with *prospect identification* (e.g.; reducing a large prospect area to smaller target areas for detailed exploration), followed by *prospect confirmation*, *reservoir assessment and confirmation*, *reservoir development*, and *field operation* (exploitation). Figure 5-1 shows that the thrust of this program is to a) survey the current state of knowledge of geothermal resources and of geoscientific methods, b) define and prioritize, with industry input, potential improvements in exploration

FIGURE 5-1

Program Logic
Exploration and Assessment Technology

and assessment, c) develop and field-test new methods and instruments, d) determine optimum exploration strategies, and e) transfer all technology to industry. Success in each step depends on attaining success in the preceding step.

The earth science components most often used to accomplish prospect identification, prospect confirmation, and reservoir assessment and confirmation are portrayed in Figure 5-2 as a complete exploration strategy. Industry generally uses only selected components depending upon individual preference, and no optimum strategy has yet been defined for any geothermal resource type or for any geologic environment. It is within the framework of Figure 5-2 that research and development in exploration and assessment technology must be accomplished. At our present state of knowledge, individual techniques, correlation of techniques through multiple data set modeling, and construction of a comprehensive system model to guide exploration and assessment drilling, all require development of new technology. Exploration and assessment technology also impacts on the reservoir development and exploitation phases as it pertains to environmental problems.

To meet the stated goals of this plan a number of program objectives, based on industry-defined needs, has been identified and classified as either near-term or mid- to far-term objectives (Tables 5-1 and 5-2, respectively). For each objective several methods of approach must be considered. These are detailed in Tables 5-3 and 5-4, and are re-stated as a set of prioritized task statements in the Technical Plan (Section 6.0). Some explanatory notes concerning the objectives are contained in Appendix 4.

FIG. 5-2
EXPLORATION STRATEGY

GEOLOGY

Structure
Lithology
Petrology/Mineralogy
Alteration
Dating

Correlate

GEOCHEMISTRY

Rocks, Fluids, Gases
Major elements
Trace elements
Isotopes
Predicted Temperatures

Correlate

GEOPHYSICS

Gravity
Magnetics
Seismics
Electrical
Thermal
Remote Sensing

Correlate

HYDROLOGY

Recharge
Flow Coupling

Correlate

Correlate → SYSTEM MODELING → DRILLING

Boundaries
Probable Producing Zones
Permeability
Porosity
Temperature bounds
Structural and/or
stratigraphic control

TABLE 5-1Near-Term Program Objectives

- Improve exploration cost-effectiveness.
- Improve locations of exploratory wells.
- Improve effectiveness of exploratory drilling.
- Improve locations of step-out (confirmatory) wells.
- Improve ability to delineate and characterize the reservoir. (Coordinate this work carefully with the Geothermal Reservoir Engineering Program.)
- Improve the transfer of technology between DOE/DGE-supported technology developers and the geothermal exploration industry.

TABLE 5-2Mid- and Far-term Program Objectives

- Improve exploration effectiveness for discovering new resources.
- Basic research.

TABLE 5-3

NEAR-TERM PROGRAM OBJECTIVES, METHODS OF APPROACH AND POSSIBLE IMPACTS

<u>Objective</u>	<u>Methods of Approach</u>	<u>Possible Impacts</u>
1. Improve exploration cost-effectiveness.	<p>(a) Develop improved exploration strategies (architecture) through careful case history analyses for several generic types of geothermal resources:</p> <ul style="list-style-type: none"> • Convective hydrothermal systems <ul style="list-style-type: none"> - Fracture controlled - Stratigraphic (sedimentary) - Combination fracture and stratigraphic • Geopressured Systems • Hot Dry Rock • Magma • Radiogenic • Normal Geothermal Gradient <p>If hard case history data are lacking, prepare exploration scenarios based on best guesses. Include case histories from foreign countries.</p> <p>(b) Associated with the exploration strategies (a), determine exploration costs and subject strategies to benefit/cost sensitivity analyses.</p> <p>(c) Identify and implement improvements in exploration technology.</p> <ul style="list-style-type: none"> • Test new or improved survey techniques for comparative information concerning costs, scientific information, etc. • Conduct field surveys using conventional techniques to complete case history background information, or if needed to verify results from new techniques. 	Improvement in exploration effectiveness could reduce front-end costs by 50%.

TABLE 5-3 (Continued)

<u>Objective</u>	<u>Methods of Approach</u>	<u>Possible Impacts</u>
	<ul style="list-style-type: none"> • Develop better and less expensive interpretation techniques, develop interpretation techniques capable of handling multiple data sets. • Develop real-time in-field data processing and preliminary interpretation to verify survey results and to guide subsequent data collection. 	
2. Improve locations of exploratory wells.	<p>(a) Develop, test and apply state-of-the-art geological, geophysical, geochemical, and hydrological technology to locate, identify, and prioritize fractures and permeable zones from the surface.</p> <ul style="list-style-type: none"> • Support field surveys at selected sites in each of the regions in cooperation with industry. • Publish results as both topical reports and as case histories. 	Improve exploratory hole success ratio by 5 to 15%.
3. Improve effectiveness of exploratory drilling.	<p>(a) Develop and demonstrate mineralogical and geochemical techniques for predicting the approach to hot water during drilling.</p> <p>(b) Develop and demonstrate methods to identify specific hot water or steam entries by means of a combination of well logs, rock geochemistry, and rock mineralogy.</p> <p>(c) Develop better, more reliable, conceptual models for reservoirs.</p>	Enable real-time decision on whether a drill hole should be deepened or terminated.
4. Improve locations of step-out (confirmatory) wells.	<p>(a) Similar to Task Description for 2, but supported by geoscience investigations of a more detailed nature.</p>	Minimize by 5 to 15% the number of unnecessary or non-productive step-out wells.

TABLE 5-3 (Continued)

<u>Objectives</u>	<u>Methods of Approach</u>	<u>Possible Impacts</u>
5. Improve ability to delineate and characterize the reservoir. (Coordinate this work carefully with the Geothermal Reservoir Engineering Program so that no duplication of work occurs and so that each program develops the technology needed by that program.)	<p>(a) Develop, test, and demonstrate new or improved methods, based on a combination of geological, geophysical, geochemical and hydrological techniques, to provide information on one or more of the following reservoir parameters.</p> <ol style="list-style-type: none"> 1. Reservoir dimensions, i.e., boundaries. 2. Temperature distribution 3. Permeability or permeability-thickness product (transmissivity). 4. Specific storativity. 5. Storage coefficient. 	Reduce economic uncertainty of reservoir at an early stage.
6. Improve the transfer of technology between DOE-supported technology developers and the geothermal exploration industry.	<p>(a) Develop better legal/contractual mechanism for transferring hardware innovations to industry and for bringing potential buyers and sellers together.</p> <p>(b) Conduct topical short-courses and workshops.</p> <p>(c) Conduct case-study symposia.</p> <p>(d) Distribute computer programs.</p>	Reduce exploration costs.

TABLE 5-4

MID- AND FAR-TERM PROGRAM OBJECTIVES, METHODS OF APPROACH AND POSSIBLE IMPACTS

<u>Objective</u>	<u>Methods of Approach</u>	<u>Possible Impacts</u>
1. Improve exploration effectiveness for discovering new resources.	<p>(a) Determine technical barriers to exploration and assessment for geothermal resources of the geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient type.</p> <p>(b) Develop, test and demonstrate new techniques needed to find as yet unspecified types of geothermal resources or for finding the totally concealed convective hydrothermal, geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient type.</p> <p>(c) Conduct, participate in, or encourage regional assessment programs that will provide the fundamental data base from which new resources may be discovered.</p> <ul style="list-style-type: none"> • Continental deep drilling program • Regional magnetotelluric surveys • Regional heat flow surveys • Deep crustal reflection and refraction surveys • Regional geology, aeromagnetic, and gravity surveys • Regional water and rock chemistry surveys 	Needed to assure a steady discovery rate.
2. Basic research	<p>(a) Identify areas where basic research is needed to satisfy the mid- to far-term geothermal energy goals.</p>	

6.0 Technical Plan

6.1 Introduction

ERDA-86, the Definition Report, provided the baseline for this technical plan. An industry-driven update to this baseline has been provided in "Program Review: Resource Evaluation, Reservoir Confirmation, and Exploration Technology" (Ward, 1978) in which specific recommendations for technology development were made. This technical plan was formulated from the above input by representatives from DOE - Division of Geothermal Energy (DOE/DGE); DOE - San Francisco Operations Office (DOE/SAN); University of California, Lawrence Berkeley Laboratory (UC/LBL); and the University of Utah/University of Utah Research Institute (UU/UURI).

The general procedure used to date, and to be followed in the future, is:

1. obtain updated input regarding barriers to commercialization of geothermal energy from industry, the Regional Managers, and from other geothermal programs,
2. from these barriers, define updated, realizable program objectives,
3. design a strategy for achieving each objective, and
4. convert the strategies to specific technical tasks for both near-term solutions and mid- and far-term solutions.

Tables 6-1 and 6-2 contain a listing of the near-term tasks and mid- and far-term tasks, respectively, which are described briefly below and for which elaboration and justification is contained in Appendix 5.

TABLE 6-1

NEAR-TERM TASKS

6.2.1 ONGOING AND RETROSPECTIVE
CASE STUDIES

- 6.2.1.1 METHODS COMMONLY USED
- 6.2.1.2 NEW OR LESS COMMONLY USED
METHODS

6.2.2 TECHNIQUE DEVELOPMENT

- 6.2.2.1 HARDWARE AND METHODS
 - 6.2.2.1.1 IN-SITU THERMAL PROPERTIES
 - 6.2.2.1.2 TEMPERATURE LOGGING
 - 6.2.2.1.3 COMPARE ELECTRICAL METHODS
 - 6.2.2.1.4 SEISMIC SYSTEM
 - 6.2.2.1.5 ROCK PROPERTIES
 - 6.2.2.1.6 BOREHOLE GEOPHYSICS
 - 6.2.2.1.7 SURFACE GEOCHEMICAL SURVEY
- 6.2.2.2 DATA ACQUISITION AND PROCESSING
 - 6.2.2.2.1 NOISE IN ELECTRICAL SURVEYS
- 6.2.2.3 DATA INTERPRETATION
 - 6.2.2.3.1 COUPLED FLOW
 - 6.2.2.3.2 GEOCHEMICAL DETECTION OF
DEEP OR BLIND PARTS OF
CONVECTIVE HYDROTHERMAL SYSTEMS
 - 6.2.2.3.3 TWO- AND THREE-DIMENSIONAL
ELECTRICAL MODEL ANALYSIS
 - 6.2.2.3.4 MULTIPLE GEOPHYSICAL DATA
SET ANALYSIS
 - 6.2.2.3.5 GEOTHERMAL EARTH SYSTEM MODELS

6.2.3 EXPLORATION STRATEGIES

- 6.2.3.1 MULTIPLE TECHNIQUE CASE STUDIES
- 6.2.3.2 BENEFIT/COST ANALYSES

6.2.4 TECHNOLOGY TRANSFER

- 6.2.4.1 WORKSHOPS
- 6.2.4.2 BARRIERS
- 6.2.4.3 COMPUTER PROGRAMS

TABLE 6-2

MID- AND FAR-TERM TASKS

<u>6.3.1 CASE STUDIES</u>	<u>6.3.2 TECHNOLOGICAL AND ASSESSMENT IMPROVEMENTS</u>	<u>6.3.3 EXPLORATION STRATEGIES</u>	<u>6.3.4 TECHNOLOGY TRANSFER</u>
6.3.1.1 RETROSPECTIVE CASE STUDIES	6.3.2.1 IMPROVE EXPLORATION EFFECTIVENESS FOR DISCOVERING NEW RESOURCES	6.3.3.1 DISCOVER HIDDEN RESOURCES	6.3.4.1 DEVELOP NEW TECHNIQUES FOR EFFECTING TECHNOLOGY TRANSFER
6.3.1.2 WORLD-WIDE CASE STUDIES	6.3.2.2 CONVERT OUTPUT FROM BASIC RESEARCH PROGRAMS TO NEW EXPLORATION TECH- NOLOGY	6.3.3.2 EXPLOIT MAGMA	

6.2 Task Descriptions, Near-Term

Due to funding limitations, not all of the identified near-term tasks will be addressed by the FY79 program. Under present planning those tasks marked below by an asterisk (*) will be funded for work by contractors through normal DOE/San Francisco Operations Office procurement procedures (see 9.0 and Figure 7-3). Work on the other tasks must await future funding.

6.2.1 Ongoing and Retrospective Case Studies

An ongoing case history is herein defined as one which is in a state of preparation but which has received little or no subsurface testing. By contrast, a retrospective case history is one written after substantial drilling has been completed at which time it is possible to assess, retrospectively, the exploration methods used.

Some exploration methods are commonly used by all industrial geothermal developers while others are less commonly used or not used intensively. There is a need to provide case studies which include both of these classes of methods as well as new or untried methods.

6.2.1.1 Methods Commonly Used *

Apply commonly used geological, geochemical, geophysical, and hydrological techniques at selected sites in each region for the purposes of:

- (1) rounding out case studies to make them comprehensive,

* To be funded by FY79 procurement (see 9.0).

- (2) providing a data base to which new or less commonly used techniques may be referenced,
- (3) providing a data base for extrapolation of applicability of methods and strategies to other areas or regions,
- (4) providing a data base for development of new methods of interpretation for the numerous geoscientific methods applied at each site, and
- (5) affording benefit/cost analyses for each method.

6.2.1.2 New or Less Commonly Used Methods *

Apply new, or less commonly used, exploration techniques at sites where comprehensive data bases already exist so that these techniques can be evaluated.

6.2.2 Technique Improvements

6.2.2.1 Hardware and Methods

6.2.2.1.1 In-situ Thermal Properties* - Develop reliable and inexpensive in-situ methods for measuring thermal conductivity, thermal diffusivity, and possibly porosity and fluid flow for the purpose of improving thermal exploration methods.

6.2.2.1.2 Temperature Logging* - Develop less expensive yet precise and portable temperature logging equipment than is currently available for use in thermal gradient holes where temperatures

* To be funded by FY79 procurement (see 9.0).

may reach 200°C. This would facilitate acquisition of more temperature data.

6.2.2.1.3 Compare Electrical Methods - Compare the most recently developed electromagnetic, resistivity and induced polarization, and MT/AMT hardware for benefits derived and cost-effectiveness.

6.2.2.1.4 Seismic System - Develop and test an improved, low-cost, computer controlled, multi-channel, passive (broad-band) seismic system for combined earthquake, P- and S-wave travel-time delays, spectral and attenuation analyses, and Poisson's Ratio studies for use in conjunction with active seismic methods to define fracture zones, zones of high porosity, areas of high temperature, and movement of fluids.

6.2.2.1.5 Rock Properties - Develop laboratory techniques for measuring rock properties under simulated reservoir conditions, and for handling brines at temperatures in excess of 250°C.

Note that this task is common to several of DOE/DGE's geothermal programs, and efforts under this task will be carefully coordinated by DOE/DGE and program participants to remove unnecessary duplication.

6.2.2.1.6 Borehole Geophysics* - Adapt and test surface-to-borehole and borehole-to-borehole geophysical methods as a means of mapping fractures and delineating reservoir boundaries.

6.2.2.1.7 Surface Geochemical Survey* - Provide a large-scale multi-element geochemical survey over and peripheral to the

* To be funded by FY79 procurement (see 9.0).

area of producing geothermal wells at a thoroughly documented site in order to test this method for detecting hidden geothermal resources.

6.2.2.2 Data Acquisition and Processing

6.2.2.2.1 Noise in Electrical Surveys* -

Identify and develop means to remove noise and instrumental problems associated with active and passive electrical methods in order to increase reliability of interpretations and depth of search.

6.2.2.3 Data Interpretation

6.2.2.3.1 Coupled Flow* - Develop methods for interpreting heat flow, fluid flow and self-potential data in terms of combined conductive/convective/gravity/chemical/electrical coupled forces.

6.2.2.3.2 Geochemical Detection of Deep or Blind Parts of Convective Hydrothermal Systems* - Address the problems of and produce solutions to refinement and development of new geochemical techniques that might be used to aid location of deep or blind parts of convective hydrothermal reservoirs.

6.2.2.3.3 Two- and Three-Dimensional Electrical Model Analysis* - Develop cost-effective, two- and three-dimensional techniques, via analytical, numerical or model tank methods, for interpreting and comparing the effectiveness of active and passive electrical/electromagnetic methods extant.

6.2.2.3.4 Multiple Geophysical Data Set Analysis*
- Develop cost-effective methods for forward and inverse modeling using

* To be funded by FY79 procurement (see 9.0).

multiple data sets simultaneously; e.g., different types of electrical/electromagnetic data sets or gravity/magnetic/seismic data sets. This work will increase the reliability of geophysical data interpretation.

6.2.2.3.5 Geothermal Earth System Models* -

Develop conceptual models of geothermal earth systems which take account of existing surface and subsurface data. Test the sensitivity of the models to the various data sets.

6.2.3 Exploration Strategies

Develop exploration strategies based on data at well-documented sites which, in a cost-effective sense, optimally combine various geological, geophysical, geochemical and hydrological methods for the various types of geothermal resources and subsets thereof.

6.2.3.1 Multiple Technique Case Studies

Develop optimum exploration strategies based on multiple technique case studies, especially retrospective case studies.

6.2.3.2 Benefit/Cost Analyses

Perform benefit/cost analyses which indeed establish that a given strategy is optimum for a particular resource type in a particular geologic setting.

6.2.4 Technology Transfer

6.2.4.1 Workshops

Conduct workshops, short courses, seminars and demonstrations wherein the state-of-the-art geothermal exploration

* To be funded by FY79 procurement (see 9.0).

technology is conveyed to industrial users. Prepare and distribute reference manuals describing one or more aspects of geothermal exploration technology. Let procurements to initiate commercial utilization of technology developed by national laboratories and universities.

6.2.4.2 Barriers

Design means to reduce institutional, legal, and economic barriers to rapid technology transfer between DOE-supported developers and the general exploration industry.

6.2.4.3 Computer Programs

Disseminate DOE/DGE funded documented computer listings of algorithms suited to solving problems arising in geothermal exploration.

6.3 Task Descriptions, Mid- and Far-Term

6.3.1 Case Studies

6.3.1.1 Retrospective Case Studies

Publish retrospective case studies which identify needed developments in exploration technology or which re-evaluate exploration strategies and methodologies.

While emphasis in the mid-term probably will be on convective hydrothermal resources, there likely will be a gradual phasing up of exploration for geopressured, hot dry rock, magma, radiogenic, normal geothermal gradient, and resource types. Hence, retrospective case studies on one or more of these resource types are expected to be necessary.

6.3.1.2 World-Wide Case Studies

Catalogue and issue world-wide case studies.

6.3.2 Technological and Assessment Improvements

Conceive, develop, and test new exploration *methodologies* for detection and delineation of concealed geothermal resources of all types and demonstrate the existence of resource types not yet recognized or not yet considered economical. Test these methodologies by deep drilling.

6.3.2.1 Improve Exploration Effectiveness for Discovering New Resources

Technological developments should permit one to conceive, develop, and test new geothermal exploration methodologies suited to detection and delineation of concealed geothermal resources. The program shall support such technology development. .

6.3.2.2 Convert Output from Basic Research Programs to Exploration Technologies

Basic research is expected to demonstrate a) the existence of resource areas not yet identified; b) the existence of resource types not yet recognized, and c) the existence of resource types not currently considered economical but with changing technology in future will be economical. The program shall support conversion of basic research output to practical exploration technologies within this framework.

6.3.3 Exploration Strategy

Conceive, develop, and test new exploration *strategies* for detection and delineation of concealed geothermal resources of all types and to demonstrate the existence of resource types not yet recognized or not yet considered economical.

6.3.3.1 Discover Hidden Resources

Based on development of new technologies and recognition of new resource types, areas, and/or economics, the program will foster development of new exploration strategies.

6.3.3.2 Exploit Magma

In order for magma to be tapped as a geothermal resource, means must be found for detecting and delineating hidden magma chambers. The program shall address this problem.

6.3.4 Technology Transfer

6.3.4.1 New Techniques for Effecting Technology Transfer

Develop improved means for technology transfer given that the newer techniques may be technically difficult to assimilate and that personnel capable of utilizing them may be scarce.

6.4 Relationships of Tasks to Objectives

In Tables 6-3 and 6-4 the objectives and tasks are correlated in matrices. Any one task might impact several objectives and, in general, each objective is addressed by several tasks.

6.5 Preliminary Identification of Basic Geoscience Research Required to Support Geothermal Exploration

As a natural consequence of identifying required near-term, and mid- to far-term *applied* research in exploration technology, items of *basic* research in the geosciences (relating to development of geothermal resources) are also identified. In Appendix 6 a preliminary listing of basic research items is made.

TABLE 6-3

	6.2.1 CASE STUDIES	6.2.2 TECHNIQUE IMPROVEMENTS								6.2.3 EXPLORATION STRATEGIES	6.2.4 TECHNOLOGY TRANSFER					
TASKS →		6.2.2.1 HARDWARE							6.2.2.2 DATA ACQUISITION, PROCESSING	6.2.2.3 DATA INTERPRETATION						
OBJECTIVES ↓		6.2.2.1.1 IN-SITU THERMAL PROPERTIES	6.2.2.1.2 TEMPERATURE LOGGING	6.2.2.1.3 COMPARE ELECTRICAL METHODS	6.2.2.1.4 SEISMIC SYSTEM	6.2.2.1.5 ROCK PROPERTIES	6.2.2.1.6 BOREHOLE GEOPHYSICS	6.2.2.1.7 SURFACE GEOCHEMICAL SURVEY	6.2.2.2.1 NOISE IN ELECTRICAL SURVEYS	6.2.2.3.1 COUPLED FLOW	6.2.2.3.2 GEOCHEMICAL DETECTION	6.2.2.3.3 2D-3D ELECTRICAL MODELS	6.2.2.3.4 MULTIPLE DATA SET	6.2.2.3.5 GEOTHERMAL EARTH SYSTEM MODELS		
IMPROVE EXPLORATION COST- EFFECTIVENESS	X	X	X	X	X			X	X	X		X	X		X	X
IMPROVE LOCATIONS OF EXPLORATORY WELLS	X	X		X	X	X		X	X	X		X	X			X
IMPROVE EFFECTIVE- NESS OF EXPLORATORY DRILLING							X	X			X					X
IMPROVE LOCATIONS OF STEP-OUT WELLS	X	X		X	X	X	X	X	X	X	X	X	X	X		X
IMPROVE ABILITY TO DELINEATE AND CHAR- ACTERIZE RESERVOIRS	X	X		X	X	X	X	X	X	X	X	X	X	X		X
IMPROVE TECHNOLOGY TRANSFER																X

TABLE 6-4

Mid- to Far-Term	Tasks	6.5.1.0 Case Studies		6.5.2.0 Technical Improvements	6.5.3.0 Exploration Strategy	6.5.4.0 Technology Transfer
	Objectives	6.5.1.1 Retrospective Case Studies	6.5.1.2 World-wide Case Studies			
	Improve exploratory effectiveness for finding new resources	X	X	X	X	X
	Identifying areas for basic research	X	X	X		

7.0 Management Plan

Figure 7-1 portrays the management structure for the Program in Geothermal Exploration and Assessment Technology. Figure 7-2 portrays the flow of information and the coordinating structure vis-a-vis other related programs. Every effort will be made a) to support the regions, b) to design minimum but essential overlap with other related programs, and c) to support interface efforts concerned with resource types other than hydrothermal.

7.1 DOE/DGE

The Manager, Exploration Technology, acting with the concurrence of the Program Manager, Geothermal Technology Development and with the concurrence of the Director, Division of Geothermal Energy (DOE/DGE) will provide overall programmatic guidance for the definition, planning, direction, and control of the Program in Exploration Technology. DOE/DGE will also provide overall financial guidance to the DOE-supported participants in the program, including subprogram-level guidance to the Geothermal Program at the San Francisco Operations Office. The Manager for Exploration Technology will be responsible for coordinating this program with national geothermal program elements contained within DOE, as illustrated in Figure 7-2, and with the USGS and other agencies participating in the national geothermal program.

7.2 San Francisco Operations Office

The Office of Geothermal Energy, San Francisco Operations Office, will provide program administration including planning assistance,

Fig. 7-1

Fig. 7-2

financial management, program coordination and integration, procurement, project review, contract monitoring/review and procurement activities.

7.3 University of Utah/University of Utah Research Institute (UU/UURI)

UU/UURI will provide administrative and technical support for exploration and assessment technology. In detail, UU/UURI will be responsible for: planning support; program implementation; assisting in program and national coordination; program documentation; supporting contract monitoring and review; obtaining and collating industry, government and academic inputs; assuring technology transfer; conducting RD & D; initiating the development of long range conceptual models of geothermal resource types; and identifying items requiring applied and basic research in support of the program.

7.4 University of California/Lawrence Berkeley Laboratory (UC/LBL)

UC/LBL will provide daily technical support to DOE/SAN, as requested, concerning technically related items as identified by DOE/DGE or DOE/SAN or as requested by UU/UURI via DOE/SAN. The UC/LBL activities may, therefore, include assistance with program planning, procurement, technology transfer, and coordination of the efforts of related programs at UC/LBL and at other national laboratories, and conducting RD & D.

7.5 Relationship to Other Programs

It will be the responsibility of DOE/DGE to ensure coordination of this program with USGS geothermal programs. DOE/DGE also will ensure coordination with regional and generic programs in hydrothermal and other

resource types as shown in Figure 7-2. UU/UURI will provide major exploration and assessment technology development support for each of the regions and for other resource types as requested by DOE/DGE, while UC/LBL will provide major support for coordinating this program with other programs in the national laboratories.

7.6 Management Milestones

Figure 7-3 contains the major management milestones for the program for FY79 and a listing of the procurements which will be let through SAN.

FIG. 7-3
MILESTONE CHART
TECHNICAL PROGRAM
FY 79

TASK		SCHEDULE FY 79			
<u>RFP</u>		1	2	3	4
6.2.1	Case Studies	▽			▽
6.2.2.1.2	Temperature Logging	▽			▽
6.2.2.1.7	Surface Geochemical Survey	▽			▽
<u>PRDA</u>					
6.2.2.1.1	In-Situ Thermal Properties	▽			▽
6.2.2.1.6	Borehole Geophysics	▽			▽
6.2.2.2.1	Noise in Electrical Surveys	▽			▽
6.2.2.3.1	Coupled Flow	▽			▽
6.2.2.3.2	Geochemical Detection	▽			▽
6.2.2.3.3	Two- and Three-Dimensional Electrical Model Analysis	▽			▽
6.2.2.3.4	Multiple Geophysical Data Set Analysis	▽			▽
6.2.2.3.5	Geothermal Earth System Models	▽			▽
Technical Review Committee Meetings		+		+	
Industrial Review Panel Meetings			+		+
Review by Regional Managers and Other Program Managers		+			+

8.0 Budget

8.1 Minimum Budget

Table 8-1 contains the planning budget for the near-term tasks which can be funded under the minimum (approved) budget for FY79. This budget permits only one year of near-term activities and no mid- or far-term activities. Hence advanced work in hydrothermal technology development and any work in geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient resource types are precluded. Only a fraction of the recommended near-term activities are funded by this budget.

8.2 Proposed Expanded Budget

Table 8-2 contains a five year budget (not approved) which allows for an expanded near-term effort, gradually phasing down over five years, and the introduction of a mid- and far-term effort which phases up over five years. The latter effort is directed largely toward detecting and delineating totally hidden convective hydrothermal resources, geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient types of resources. Figure 8-1 portrays the decay of near-term and the growth of mid- and far-term activities over the five year interval.

TABLE 8-1
MINIMUM BUDGET

<u>Task Descriptions</u>		<u>FY 79</u>
<u>Near-Term</u>		
6.2.1	Case Studies	\$ 400K
6.2.2.1.1	In-situ Thermal Properties	25K
6.2.2.1.2	Temperature Logging	50K
6.2.2.1.6	Borehole Geophysics	150K
6.2.2.1.7	Geochemical Survey	30K
6.2.2.2.1	Noise in Electrical Surveys	100K
6.2.2.3.1	Coupled Flow	75K
6.2.2.3.2	Geochemical Detection	75K
6.2.2.3.3	Electrical Modeling	100K
6.2.2.3.4	Multiple Geophysical Data Set Analysis	80K
6.2.2.3.5	Geothermal Earth System Models	75K
		<hr/> \$1160K

TABLE 8-2

PROPOSED EXPANDED BUDGET

TASK DESCRIPTIONS	FY 79	FY 80	FY 81	FY 82	FY 83
<u>Near-Term</u>					
1.0 Case Studies	\$1500K	\$1500K	\$1000K	\$ 500K	\$ 300K
2.0 Technique Improvements					
2.1 Hardware	1000K	1500K	1500K	500K	-
2.2 Data Acquisition and Processing	200K	200K	200K	-	-
2.3 Data Interpretation	500K	1000K	1500K	1000K	300K
2.4 Earth System Models	100K	200K	500K	1000K	1200K
3.0 Exploration Strategies	200K	200K	100K	100K	100K
4.0 Technology Transfer	200K	200K	200K	200K	200K
Totals	3700K	4800K	4500K	3300K	2100K
<u>Mid- and Far-Term</u>					
1.0 Case Studies	-	-	500K	1000K	1500K
2.0 Technique Improvements	200K	500K	1000K	2000K	4000K
3.0 Exploration Strategy	-	-	200K	500K	500K
Totals	200K	500K	1700K	3500K	6000K
Grand Totals	\$3900K	\$5300K	\$6200K	\$7000K	\$8100K

9.0 Procurement Plan

9.1 Minimum Budget

Figure 7-3 contains the milestones for FY79 under the currently approved budget. Expenditures for near-term objectives under a fully funded program are forecast in Table 8-2. The figures in Table 8-1 are readily interpreted to reflect a low level but significant impact during FY79 on the attainment of the program objectives and goals.

It is anticipated that one PRDA and three RFP's will be issued under this program of minimal-level funding. The RFP's will cover procurement for near-term tasks 6.2.1 Case Studies, 6.2.2.1.2 Temperature Logging, and 6.2.2.1.7 Surface Geochemical Survey whereas the PRDA will cover procurements for 6.2.2.1.1 In-Situ Thermal Properties, 6.2.2.1.6 Borehole Geophysics, 6.2.2.2.1 Noise in Electrical Surveys, 6.2.2.3.1 Coupled flow, 6.2.2.3.2 Geochemical Detection, 6.2.2.3.3 Two- and Three-Dimensional Electrical Model Analysis, 6.2.2.3.4 Multiple Geophysical Data Set Analysis, and 6.2.2.3.5 Geothermal Earth System Models. Figure 9-1 contains the procurement schedules and responsibilities for the RFP's and PRDA.

9.2 Proposed Expanded Budget

Should an expanded budget become available, then a procurement plan suited to the expanded budget would need to be developed.

FIGURE 9-1

RFP & PRDA PROCUREMENT SCHEDULE & RESPONSIBILITIES

Acknowledgements

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The input of industry, government, and academic professionals to the Plan is described in detail herein and is gratefully acknowledged.

REFERENCES

- Anonymous, 1977, Geothermal reservoir engineering management program plan (GREMP plan); LBL Report LBL-7000, UC-66a, TID-4500-R66, Oct. 1977.
- Bamford, R. W., 1978, Geochemistry of solid materials from two U.S. geothermal systems and its application to exploration: UURI, ESL Report, DOE Contract EY-76-S-07-1601, 196 p.
- Capuano, R. M., (in press), Initial investigation of soil mercury geochemistry as an aid to drill site selection in geothermal systems: UURI, ESL Report, DOE Contract EG-78-C-07-1701.
- Dhillon, H., A. El-Sawy, S. Goldstein, T. Meidav, and R. Pfundstein, 1978, Benefit-cost analysis of the Federal reservoir exploration, assessment and confirmation program: Mitre Corporation, METREK Division, in preparation.
- Goldstein, N.E., R.A. Norris, and M.J. Wilt, 1978, Assessment of surface geophysical methods - geothermal exploration and recommendations for further research: UC/LBL Report 6815, DOE Contract W-7405-ENG-48, April 1978.
- Goubau, W. M., T. D. Gamble, and J. Clarke, (1978), Magnetotelluric data analysis: Removal of bias, 1157 p.
- Klushman, R. W. and R. A. Landress, 1977, Nature of the occurrence of mercury in the soils of geothermal areas: Co. School Mines, Dept. of Chemistry and Geochemistry, Final Report, USGS Grant #14-08-0001-G-335, 116 p.
- Mathews, M., P. R. Kintzinger, A. W. Laughlin and J. C. Maxwell, 1978, Draft plan of the geothermal log interpretation development program plan: LASL Report.
- Matlick, J. S., III and P. R. Buseck, 1976, Exploration for geothermal areas using mercury: a new geochemical technique: Proceedings of 2nd U N Symposium on Development and Use of Geothermal Resources, Pezzotti, C. (ed.): U.S. Govt. Printing Office, v. 1, p. 785-792.
- Newsom, M.M., J.H. Barnette, L.E. Baker, S.G. Varnardo, and J. Polito, 1978, Geothermal well technology--drilling and completion program plan: Sandia Report 77-1630, printed March, 1978.
- Parry, W. T., N. L. Benson, and C. D. Miller, 1976, Geochemistry and Hydrothermal Alteration at Selected Utah Hot Springs, Dept. of Geol. and Geophys., Univ. of Utah, Final Report, v. 3, NSF Contract GI-43741, 131 p.

Smith, J.C., C. F. Isselhardt, and J.S. Matlick, 1978, Summary of 1977 geothermal drilling--western United States: Geothermal Energy Magazine, v. 6, no. 5, p. 11.

Ward, S.H., 1977, Geothermal exploration architecture: Univ. of Utah, Dept. of Geol. and Geophys., Report EY-76-S-07-1601, vol. 77-2, April, 1977.

Ward, S.H., 1978, Program review: resource evaluation, reservoir confirmation, and exploration technology: U.U. Dept. Geology and Geophysics Report 78-1701-b.5.1, May, 1978.

APPENDIX 1

TECHNICAL AND ECONOMIC BARRIERS TO
HYDROTHERMAL COMMERCIALIZATION

This appendix explains and amplifies the technical and associated economic barriers which face industry in efforts to commercialize hydrothermal systems.

1.1 Drill site selection techniques for discovery, assessment, confirmation, and production drilling are poor so that far too many "dry" holes are drilled.

According to Smith, et al., (1978), 25 of 47 wells drilled for production during 1977 "appear to have found at least potentially commercial amounts of steam or hot water." This is a success rate of 53%. Significantly, however, 39 of these 47 holes were drilled in the Geysers or in the Imperial Valley, where much more knowledge and experience exist for drill-site selection than in the typical project or field. More typical success ratios outside of well-known areas have been estimated at 21 per cent (see page 9).

The problems associated with drill-site selection change with progressing maturity in the development of a hydrothermal field. During early stages, heavy reliance must be placed on surface geology, geophysics, geochemistry and hydrology. Drilling even at the stage of reservoir confirmation still relies on these techniques.

Most of today's geothermal resource exploration and assessment technology has been acquired from mineral, gas and oil exploration.

Reliable surface exploration and assessment methods designed specifically for locating subsurface concentrations of heat and water are only developing, and difficulties are encountered where there are few or no surface manifestations. There are many exploration and assessment techniques that are available for use prior to deep drilling. Geological, geophysical, geochemical, and hydrological data and information in various forms and extent can be obtained from surface and shallow hole measurements and used to locate geothermal resources. It is difficult to determine, comprehensively, the strengths and weaknesses of these techniques for the following reasons: the resource could be situated in a variety of geological structures and rock types; too few usable reservoirs have been found to provide sites for test and evaluation of improved techniques and instrumentation; and the technology currently in use or potentially available is complex. There is a need to be able to correlate the data of various exploration and assessment techniques with the reservoir characteristics determined by deep drilling to improve the interpretation of surface and near surface measurements. The current lack of a reliable exploration technology and the necessity for deep drilling make geothermal exploration a costly, high-risk undertaking. The lack of adequate exploration and assessment technology also hampers the process of estimating accurately the regional and national geothermal potential of the United States. Improvements in surface and shallow hole assessment and exploration technology are necessary to increase the accuracy of prediction for both resource assessment by the Federal Government and exploratory site selection by industry. Such efforts could improve the success ratio in exploratory drilling and thereby improve the economics of exploration.

1.2 Reservoir delineation (in terms of reservoir limits, depth, temperature, and quantity and properties of contained fluid) by surface geoscience observations and shallow drilling methods is unreliable.

At the present time there is no reliable way to determine extent, depth, temperature, nature of fluid, or productivity of a potential geothermal resource -- without a number of deep drill holes which actually sample the reservoir. Yet deep drilling costs, especially in the reservoir rocks themselves, are very high. Accordingly, there would be a large cost benefit to geothermal development if less expensive surface and/or shallow drilling techniques could be used to make reservoir predictions or to extend substantially the data derived from fewer boreholes.

A number of the geoscience methods offer promise. Geochemical and isotopic thermometry show promise of reliable remote prediction of reservoir temperatures, but these techniques are still being developed. Electrical geophysical methods are potentially capable of detecting hot saline fluids in porous rocks and thus showing the current extent and depth of a reservoir, but unambiguous data interpretation has not been achieved. Other methods offer hope to solve parts of the total problem.

1.3 Conceptual models of reservoirs are unreliable.

The reservoir engineer has obvious need for good reservoir models upon which to base predictions of longevity and other parameters and to formulate production development plans. It is perhaps also obvious that the geoscientist involved in searching for or developing a reservoir also has urgent need of good reservoir models. When physical and chemical property values are assigned to the components of such models, they can be

used to predict the expected surface, surface-to-borehole, and borehole-to-borehole response of the geological, geophysical, geochemical, and hydrological techniques which research geoscientists are trying to refine. Improvements in exploration tools could be developed much more rapidly if reliable reservoir models existed because these models, coupled with suitable numerical or analog analyses, could more quickly sort the many questions for potential technique improvement and thus allow the geoscientist to concentrate on the most fruitful means of attack.

1.4 Discovery costs are excessive and methods are of uncertain reliability.

In the discovery process, surface methods initially must be used alone to predict the existence of a geothermal reservoir. Generally these methods begin with reconnaissance techniques for identifying small areas of high discovery potential within large favorable areas, and then proceed to more detailed exploration of these smaller areas prior to deep drilling. At present there is no way to predict from surface or shallow subsurface measurements the existence of a geothermal resource which has no obvious surface manifestation except by very detailed and costly data collection including shallow- and intermediate-depth drilling. Exploration techniques used today for geothermal resource discovery were almost entirely developed for petroleum or for mineral exploration. Little research or technology development has taken place to date to tailor exploration techniques or combinations of techniques specifically to geothermal discovery.

It is apparent that by optimizing exploration, substantial cost savings could be realized. At the same time, increased reliability of

used to predict the expected surface, surface-to-borehole, and borehole-to-borehole response of the geological, geophysical, geochemical, and hydrological techniques which research geoscientists are trying to refine. Improvements in exploration tools could be developed much more rapidly if reliable reservoir models existed because these models, coupled with suitable numerical or analog analyses, could more quickly sort the many questions for potential technique improvement and thus allow the geoscientist to concentrate on the most fruitful means of attack.

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It is apparent that by optimizing exploration, substantial cost savings could be realized. At the same time, increased reliability of

existing methods and development of new methods will be necessary if the estimated, now unknown, 200-hydrothermal convection systems are to be located which will be needed by industry to achieve the mid- and far-term power goals of the Federal geothermal program.

1.5 Transfer of technology to industry from the national laboratories, universities, private foundations, and private contractors needs stimulating.

Because the purpose of the Federal involvement in geothermal development is the fostering of a viable geothermal industry, it is particularly important that new technologies are quickly and effectively transferred to industry for its use. The conventional techniques of technical reports, and workshops are appropriate but inadequate. New means of making technology transfer both timely and effective need to be found.

APPENDIX 2

INDUSTRY COSTS FOR EXPLORATION AND ASSESSMENT

(HYDROTHERMAL SYSTEMS)

(After Section 6.0 of Ward, 1978)

As one industrial representative notes, "Industry does not currently know how to look for geothermal resources nor what tools to use in the search". This comment was directed toward potential geothermal resources which exhibit surface manifestations. Detection and delineation of totally hidden geothermal resources is an even harder problem -- a problem explorationists are not well equipped to handle at the present time.

Table A2-1, developed with the assistance of Bob Greider of Intercontinental Energy Corporation, shows a breakdown of exploration and assessment costs associated with proving the existence of a high-temperature ($T > 200^{\circ}\text{C}$) hydrothermal field capable of 200 MWe of electrical power production. Geoscience costs (1a, 1b, 3a, 4 of Table A2-1) total \$6.34M, whereas drilling costs (3b of Table A2-1) total \$9.63M for a grand total expenditure of about \$16M for exploration and drilling.

Table A2-2 lists the capital costs of developing the field once it is proven and of installing the physical plant. In developing the field, 50 wells are to be drilled with the historical expectation that one in five will be dry. Thus ten wells at a cost of \$7.5M will be wasted or converted to reinjection wells. If wasted, the total costs of items which might be

Exploration and Assessment Cost Estimate

200 MWe Hydrothermal Field

		<u>\$Cost</u>
1a. Geology & Geophysics: 64 areas (\$50,000)	=	\$ 3,200,000
Additional Geophy: 32 areas (\$15,000)	=	480,000
1b. Temperature holes: 24 areas (\$40,000)	=	<u>960,000</u>
		\$ 4,640,000
2. Land Acquisition: 7500 acres x 29 areas		
@ 7.00/acre	=	\$ 1,523,000
7500 acres x 3 areas		
@ 70.00/acre	=	<u>1,575,000</u>
		\$ 3,098,000
3a. Detailed Geology, Geochemistry, Geophysics 16 areas @ \$75,000.00	=	\$ 1,200,000
3b. Drilling & Testing 5000' Depth		
12 Failures (\$365,000)	=	\$ 4,380,000
3 Failures w/casing run @ (\$750,000)	=	2,250,000
1 Discovery Plus 3 Confirmation @ (\$750,000)	=	<u>3,000,000</u>
		\$ 10,830,000
4. Fault Pattern Definition		\$ 500,000
High Resolution Seismic		
Isotope Studies		
Modeling		
5. Environmental Studies and Associated Costs	=	\$ 300,000
6a. TOTAL EXPLORATION GEOSCIENCE COSTS (1a, 1b, 3a, 4)	=	\$ 6,340,000
6b. TOTAL EXPLORATION DRILLING COSTS (3b)	=	9,630,000
6c. LAND ACQUISITION COSTS (2)	=	3,098,000
6d. ENVIRONMENTAL COSTS (5)	=	<u>300,000</u>
6e. TOTAL COSTS TO PROVE FIELD EXISTENCE	=	\$ 19,368,000

TABLE A2-2
CAPITAL COST ESTIMATE

Hot Water Flash 200 MWe Plant

	<u>Capital Investment</u>
<u>Steam Production</u>	\$ 47,500,000
Wells 50 @ \$0.75 M	
Surface Gathering, Collectors, Separators, Testing \$10M	
<u>Generating Plant</u>	100,000,000
Turbines, Condensors, Ejectors	
Buildings, Water Treatment (@25M/50MWe)	
<u>Substations and Transmission Lines</u>	5,000,000
<u>Total Direct Investment</u>	152,500,000
<u>Contingency and Working Capital Costs (15%)</u>	21,375,000
<u>Exploration Costs (From Table A2-1)</u>	19,368,000
<u><u>Total Costs</u></u>	<u><u>\$193,243,000</u></u>

Capital Cost \$966/Kw

reduced by improved and less expensive exploration technology is \$23.5M (\$16.0M in exploration and assessment costs and \$7.5M in wasted well costs) or a maximum of 12% of the capital costs of the unit. Optimistically, one would hope to recover about half of this \$23.5M by improvements in exploration and assessment technology.

If the capital costs are correct then they represent \$966 per KWe. Greider advises that the range \$400 to \$700 per KWe is more likely; then if we reduce capital costs to say \$550 per KWe, then costs which might be reduced by improved and less expensive technology become 21% of capital costs. Hence there is a good cost justification for improving exploration technology. As we proceed from prospects with surface manifestations to totally hidden prospects, the percentage of exploration costs relative to capital costs will rise rapidly.

The cost of time delays occasioned by inferior exploration technology has not been accounted for above, but it is a factor which warrants serious consideration.

APPENDIX 3

BENEFIT/COST ANALYSIS FOR EXPLORATION AND ASSESSMENT TECHNOLOGY
(HYDROTHERMAL SYSTEMS)

Exploration and assessment technology plays a major role in the first phase of a geothermal development project, namely, in efforts to prove the existence of a field. Typically, the first phase requires risk capital of about 10 percent of the total plant cost. This initial investment should be amenable to significant reduction in three important areas:

1. more efficient exploration well siting, resulting in fewer dry wells, and in completions in the best producing formations,
2. improved reservoir performance predictions, and
3. reduced drilling costs.

This section addresses the first item entirely and the second item in part. Programs in reservoir engineering technology development and in reduction of drilling and completion costs have already been established (Anon, 1977; Newsom et al., 1978).

Appendix 2 of this Plan contains a cost estimate of industry's expenditures for discovery and assessment of a 200 MWe hydrothermal field. Referring to Table A2-1 of Appendix 2, it is seen that about \$200 million is the total cost for a developed field, and about \$20 million is the cost required to prove the field. Thus 10 per cent of the total cost represents the risk capital required to interest major investors in supporting the

project. Under the present tax structure, this advance investment will not earn interest or return on investment (ROI) until the field begins to generate revenue. Therefore, exploration companies have a substantial need to reduce the required risk capital and to reduce the time required to make a "Go" decision for continued development of a given field.

Referring to Table A2-1 of Appendix 2, the total costs for geoscience work in Phase I are:

Reconnaissance exploration	\$4,640,000
Detailed exploration	1,200,000
Fault pattern definition	<u>500,000</u>
	\$6,340,000

These exploration and assessment costs can be reduced through (1) development of new techniques or of better ways to use existing techniques, (2) optimized exploration strategies, and (3) attainment of much better reservoir models. By using optimally combined cost-effective field methods and multiple-data-set interpretations, it is estimated that these geoscience costs could be cut in half.

Improvement in exploration reliability will reduce the number of dry exploratory wells, resulting in an increase in the drilling success ratio. Part 3b of Table A2-1 in Appendix 2 shows the present exploration and assessment drilling success ratio¹ to be 4/19 or 21 percent. The example

¹Success ratio = number of successful holes/total number of holes, where a successful hole is an exploration, assessment, or confirmation hole which intercepts potentially commercial quantities of hydrothermal fluid.

below shows the benefit of drilling success ratios of 26, 31, and 36 percent, or an improvements in the present drilling success ratio by 5, 10, and 15 percent respectively (Dhillon et al., 1978).

This example is carried out in 1978 dollars over a twenty-year period. The benefits are then normalized to fit a 200 MWe field. The example takes into account a 5% escalation in the cost of drilling and a 5% rate to discount the effect of benefits of the long term (benefits derived in latter years of the scenario). The benefits shown result from wells not drilled because of reduction in dry or wasted wells. The number of successful wells to prove the field is held constant. The benefits of improved drilling success ratios are compared as follows:

<u>TECHNOLOGY/SUCCESS RATIO</u>	<u>COST OF WELL FAILURES (\$)</u>	<u>NET BENEFIT (\$)</u>	<u>REMARKS</u>
Current Technology 21% Success Ratio	12,040,000	-0-	12 uncased failures @ \$655,100 each
Improved Technology 26% Success Ratio	9,180,000	2,860,000	9 uncased failures 2 cased failures
31% Success Ratio	7,015,000	5,025,000	7 uncased failures 2 cased failures
36% Success Ratio	4,774,000	7,266,000	5 uncased failures 1 cased failure

When these benefits are added to the estimated 50% reduction in exploration costs (\$3,170,000) total expected savings of \$6,030,000, \$8,195,000, \$10,436,000 result. These savings over present day costs are equivalent to total cost benefits of 30, 41, and 52 percent, respectively, applied to the \$19,368,000 necessary to prove the field's existence.

In addition to the above cost savings, the time-value of money not required but instead made available for other investment can be determined as follows:

If a company invests \$20 million in exploration and assessment drilling to demonstrate field potential and to stimulate further funding, then that money is not available to earn interest or return until the field starts producing. Thus interest and ROI are lost annually until a plant is put on line. Typically, 7 percent interest and 10 percent ROI may be lost. Annual losses of this kind under the assumptions of 21%, 26%, 31% and 36% drilling success ratio and in 50% savings in exploration costs for the latter 3 cases are tabulated as follows:

Table A3-1

	Current (21%)	26%	31%	36%
Exploration and Assessment Costs	19,400,000	13,300,000	11,200,000	8,900,000
7% Interest	1,400,000	900,000	800,000	600,000
10% ROI	1,900,000	1,300,000	1,100,000	900,000
Total annual loss	\$ 3,300,000	\$ 2,200,000	\$ 1,900,000	\$ 1,500,000

Thus, \$3.3 million or about 2 percent of total plant capitalization lost is presently lost each year that full development is delayed for reasons such as reservoir scale, environmental concerns and institutional problems. If a drilling success ratio of 36 percent could be achieved and if exploration geoscience costs could be halved, only \$1.5 million or about 1 percent of plant capitalization would be lost each year of delayed development.

Finally, if one is to raise some \$200 million in capital for a 200 MWe facility, some assurance of reservoir longevity must be provided. Improved exploration and assessment technology and improved reservoir engineering are the only way to provide this estimate of the longevity of a reservoir.

APPENDIX 4

PROGRAM OBJECTIVES

4.1 Near-Term Program Objectives

4.1.1 Improve Exploration Cost Effectiveness

Reconnaissance and semi-detailed surface exploration techniques are used to locate areas which have high potential for existence of a geothermal resource at depth. Because most exploration techniques are expensive and because the converging lines of evidence required to justify a drill hole usually necessitate positive results from more than one technique, surface exploration costs can be great. At the same time present techniques are sufficiently ambiguous that there is no guarantee that drill holes spotted on positive geoscience evidence will indeed intersect a geothermal resource. It is likely that certain techniques and certain combinations of techniques will ultimately be shown to be more effective than others, although industry presently can reach little consensus on this topic. There is an obvious need for improved exploration techniques and improved exploration architecture in each of the several geothermal environments in the United States.

4.1.2 Improve Siting of Exploratory Wells

As demonstrated in Section 3.0 and Appendix 3 of this plan, substantial economic benefits would result from improvements in ability to locate properly exploratory or step-out wells. The term "exploratory well" is used to mean a well drilled for the purpose of demonstrating geothermal

fluids of economic interest, i.e. before a recognized discovery has been made. The stages of exploration prior to discovery are critical because of the limited number of wells management is generally willing to fund and because of the relatively great likelihood at present of improper location of these first few wells. Reservoirs can be missed easily.

Currently there is no surface method for unambiguously determining the presence or absence of geothermal fluids at depth without drilling. Detection of geothermal resources at depth from surface observations and from shallow holes is in an infant stage. Because so much work remains to be done in documenting application of known methods to geothermal problems, in improving known methods specifically for geothermal application, and in developing new methods for exploration, the assumption that better well sitings can result from scientific technique development is a valid one. The best approach currently seems to be integrated interpretation of specific sets of geoscience data in terms of locating producing fractures or horizons at an early stage.

4.1.3 Improve Effectiveness of Exploratory Drilling

Because drilling is by far the most expensive step in confirming a geothermal reservoir, development of means to supplement and partly replace deep drill hole information in determining the size, productivity and longevity of a reservoir would be a major contribution.

The effectiveness of drilling could be improved considerably if real-time drilling decisions could be better made. Certain solids geochemistry, mineralogy and well logging methods indicate promise for

improving our ability to make real-time decisions by indicating possible approach to geothermal fluids. Thus decisions on how far to drill and whether or not a potential hot fluid entry has been "mudded-up" are possible.

4.1.4 Improve Locations of Step-Out (Confirmatory) Wells

Once the first wells have discovered a geothermal resource, the next problem is in delineating the reservoir with a minimum of wells. The discussion in Section 3.0 and Appendix 3 shows the benefits to be derived from reduction in the number of wasted wells. The basic problem generally is in tracing productive fractures or horizons. Detailed surface surveys, often similar to those used for exploration and reservoir delineation are generally employed. However, better techniques can very likely be developed.

4.1.5 Improve the Ability to Delineate and Characterize the Resource

New, effective, surface and subsurface methods are needed to help determine reservoir dimensions, temperature distribution, and nature and produceability of stored fluids. Work under this objective will be carefully coordinated with ongoing technology development in reservoir engineering (Anon., 1977) and well log interpretation (Mathews, et al., 1978).

4.1.6 Improve the Transfer of Technology between DOE-Supported Technology Developers and the Geothermal Exploration Industry

Effort and ingenuity are required to make technology transfer effective. What industry needs is technical reporting and workshops which address solutions to problems which they have in exploration and assessment technology. New and novel methods of technology transfer are also needed.

4.2 Mid- and Far-Term Objectives

4.2.1 Improve Exploration Effectiveness for Discovering New Resources

In order to reach the rather ambitious power and direct heat utilization goals which the Federal geothermal program has specified, new resources of several kinds must be found. Industry must become proficient in discovering hydrothermal resources which have no surface manifestation, and in defining areas of highest potential for discovery of geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient resources. In order to devise an effective exploration strategy, a geologic concept of the geothermal target must be the guide. Because of the relative infancy of geothermal exploration it is expected that not all of the reservoir types and environments that actually exist in nature have been studied yet. By geoscience reasoning from what is known, and by study of case histories the existence of new geothermal reservoir types or environments can be expected to be inferred, and then exploration strategies can be devised to explore for these new targets. This sequence of reasoning has proved successful in both petroleum and minerals exploration, and success in geothermal exploration can hence be anticipated.

4.2.2 Basic Research

During performance of the scientific work to accomplish the goals of this Program, research topics will become apparent whose solution would contribute substantially to mid- and far-term development of geothermal energy. It is important that these items be identified and prioritized to facilitate research projects funded by DOE, the USGS, and by other federal and state agencies and by industry.

APPENDIX 5

TASK DESCRIPTIONS WITH JUSTIFICATIONS6.2.1 Ongoing and Retrospective Case Studies6.2.1.1 Methods Commonly Used

Industrial geothermal exploration companies repeatedly have requested that the Division of Geothermal Energy of the Department of Energy (DOE/DGE) procure geoscientific case studies at selected sites in the U.S. Industry's concern is associated with its need to evaluate geothermal exploration methods and strategies in order to establish the most cost-effective approach to exploration for convective hydrothermal resources. Mapping of fractures and fracture sets is of prime concern. To a certain extent the DOE/DGE Industry-Coupled Program of providing matching funds for bottom-hole and exploration costs in return for geoscientific and other data (which are then put into the public domain) achieves this objective. However, industry is admittedly timid in its commitments to extensive and intensive geoscientific exploration because of uncertainties concerning which method or combination of methods is most cost-effective in a given geologic environment, and because it is experiencing difficulty in applying all of the methods it would prefer, and at times any one method intensively, due to cost constraints. Thus the Industry-Coupled Program transfers to industry in general the limited geoscientific efforts that one of its members has applied at a particular site. While the Industry-Coupled Program provides some funds to contractors for rounding out the data sets that industry contributes to the program for publication,

these funds are restricted to a minimal effort designed to obtain only the most critical data. As a result, the Industry-Coupled Program seldom provides the complete geoscientific data set that would be desirable for a particular area. Therefore, the Exploration and Assessment Technology Program will select a very few (perhaps 6 to 10) sites to apply, intensively, a wide range of commonly used methods for the purposes of:

- 1) rounding out comprehensive case studies,
- 2) providing a data base to which new or less commonly used techniques may be referenced,
- 3) providing a data base for extrapolation of method and strategy applicability to other areas or regions,
- 4) providing a data base for development of new methods of interpretation for the numerous geoscientific methods applied at each site, and
- 5) affording benefit/cost analyses for each method.

6.2.1.2 New or Less Commonly Used Methods

When a new exploration method is developed it must be applied at a range of convective hydrothermal test sites for which substantial data acquired by commonly used methods, including drilling, already exist to provide ground truth in three dimensions. In this manner, an evaluation and benefit/cost analysis of the new method may be performed. In a like manner, certain existing methods which infrequently have been

applied to geothermal exploration at convective hydrothermal test sites, or have not been applied intensively, require evaluation and benefit/cost analysis at several selected convective hydrothermal sites.

6.2.2 Technique Improvements

6.2.2.1 Hardware & Methods

6.2.2.1.1 In-situ Thermal Properties

The principal rock thermal property generally measured is thermal conductivity. By multiplying observed temperature gradient in a hole by thermal conductivity, the heat flux, which is a more meaningful quantity, is obtained. The present practice of making thermal conductivity measurements on core or chip samples in the laboratory has at least three drawbacks: (1) the chips or core may not be representative of the same material in situ, (2) corrections must be made for the bulk porosity which may not be known and, (3) results are delayed while samples are transported to the laboratory and prepared for measurement. A more cost-effective and satisfactory approach would perhaps utilize rapid, reliable and accurate *in-situ* measurements of thermal conductivity. Additionally, there is need for the concurrent measurement of thermal diffusivity, porosity, and fluid flow parameters.

Insofar as thermal gradients are now measured in holes ranging from 1m to 600m, different technologies for determining thermal conductivities in situ may be necessary for various parts of this depth range. Further, some measurements will be made in cased holes and others in uncased holes. The holes may range from 1.5 inch to 13.5 inch diameter. The effects of PVC

and steel casing, the effects of grout and backfill, and the effects of fluid in and behind the casing need to be evaluated.

6.2.2.1.2 Temperature Logging

At the present time it is impossible to purchase a back-pack portable temperature logging unit capable of measuring temperature to $\pm 0.01^{\circ}\text{C}$ off the shelf. Yet this is the standard unit used by many industrial, governmental, and academic workers. Presently, each worker must fabricate his own at a cost much higher than production line models would run and seldom with adequate provision for back-up leasing, repair, or purchase should a field unit fail.

With the current trend by industry to drill several heat flow holes to 600m, temperature of 100°C and greater may be encountered often. At present this requires use of an expensive well-log service because the cable and O rings used in existing back-pack portable units will not stand such temperatures.

6.2.2.1.3 Compare Electrical Methods

No new hardware procurements, for electrical methods, are contemplated under this program plan because of:

- a) the current development and testing of the EM60 electromagnetic system by Lawrence Berkeley Laboratory under DOE/DGE funding
- b) the current development of a portable electromagnetic system by Westinghouse GeoResearch under DOE/DGE funding,
- c) the current development of a versatile, broad-band,

state-of-the-art AMT/MT system by University of Texas, Austin, under DOE/DGE funding,

- d) the current development and testing of a low-noise cryogenic MT system by Lawrence Berkeley Laboratory under DOE/DGE funding, and
- e) the existence of state-of-the-art induced polarization and resistivity systems.

What is required are procurements which a) will establish and transfer to industry the comparative capabilities of these systems via adequate field testing of them, and b) will ensure that techniques developed under items a), c) and d) are transferred to a manufacturer.

Industry is in a quandry as to which electrical method or combination of electrical methods to use in geothermal exploration and desperately needs the comparative studies and subsequent technology transfer.

6.2.2.1.4 Seismic System

Recommended under 6.2.1.2 above is a case study of the cost-effectiveness of high resolution seismic methods. Such methods are expensive but do provide data of exceptional quality and engineering value. A potentially viable alternative to the high resolution seismic reflection method is a combination of seismic refraction and one or more of the passive seismic methods. Therefore it is proposed that Lawrence Berkeley Laboratory issue a procurement which would finance a comprehensive development program wherein seismic refraction, microearthquake, and teleseismic P- and S-wave delay surveys would be run concurrently. Such a package does not exist and yet, if it could be used as a substitute for

high resolution seismic surveys, it would do so at an estimated 50% of the cost. An assessment of the signal-to-noise problems of active and passive seismic methods would be an integral part of the development. This task is intended to exploit and place in industry's hands the Lawrence Berkeley Laboratory achievements in this scientific area.

6.2.2.1.5 Rock Properties

If more were known about the chemical and physical properties of cores and cuttings, better interpretations of surface geoscientific data would result and this would, in the near-term, accelerate reservoir development of convective hydrothermal systems by facilitating the placement of exploratory wells in optimum locations, thereby reducing the number of dry holes.

If the physical properties of the host rocks were better understood, better design of hydrofracturing would result and this would accelerate power-on-line in the near-term. Also, better understanding of physical and chemical rock properties would provide control information on subsidence and on induced seismicity.

Understanding of the physical and chemical properties of rocks occurring in geopressured, hot dry rock, magma, normal geothermal gradient, and radiogenic resource types also is required and on various time scales.

This facet of the program requires careful coordination with the programs in Log Interpretation, Well Stimulation, Reservoir Engineering, Subsidence, Induced Seismicity, Hot Dry Rock and with the Regional

programs. Once this coordination has been accomplished, a specific procurement plan should be developed for each of these programs.

6.2.2.1.6 Borehole Geophysics

Geophysicists define *borehole logging* as utilization of transmitters and sensors downhole for the express purpose of identifying the lithology, mineralogy, porosity, structure, etc. in the immediate vicinity (one to ten meters) of the well bore. This definition follows that used by professional petroleum well log analysts. Geophysicists define *borehole geophysics* as utilization of a combination of transmitters and sensors deployed either totally down one hole, partially down one hole and partially down another, or via a combination of downhole and surface deployments so as to explore to distances of 100m or more from the well bore. Borehole geophysics is seldom used in petroleum exploration but is applied widely in mining exploration.

A vital need exists in the geothermal industry to develop techniques which can map fractures offset from a dry well so that justification for hydrofracturing or for additional drilling can be gained. Additionally, the three-dimensional mapping of fracture systems passing through one or more producing wells, so as to indicate the optimum locations for step out wells, also is vital to the geothermal industry.

Hence, a procurement is required which will address the adaptation of existing borehole geophysical techniques (eg. resistivity, induced polarization, electromagnetics, active seismic) to mapping fractures in convective hydrothermal systems. One approach to this problem was tried in

the Hot Dry Rock program but much more effort is required if it is to lead to cost-effective exploration systems of general applicability. This task is to be coordinated with ongoing development in the Geothermal Log Interpretation Program.

6.2.2.1.7 Surface Geochemical Survey of a Convective
Hydrothermal System Using Rapid High Density
Solids Sampling and Multi-element Analyses

The use of surface solids geochemical techniques to explore geothermal systems and to provide results useful for the selection of exploration well locations requires that relatively high density sampling be carried out over large areas and that the samples collected be analysed for an adequate spectrum of useful trace elements. Several studies have provided indications that solids geochemistry should be useful in this application (Bamford, 1978; Capuano, 1978, in press; Klushman and Landress, 1977; Parry et al., 1976; and Matlick and Buseck, 1976) but have not addressed the problem of providing optimum methods for rapid sampling and multi-element analysis. Nor have they provided adequately comprehensive tests of the approach by attempting full scale multi-element surface surveys over known geothermal resources. The technique could be very important in discovering concealed resources.

6.2.2.2 Data Acquisition and Processing

6.2.2.2.1 Noise in Electrical Methods

Types of noise in electrical methods include cultural

noise (fences, pipelines), disturbance field noise (geomagnetic perturbations, atmospheric discharges, power lines), instrument noise, and geologic noise (those anomalies arising in geologic features present in the environment but which bear no relation to the geothermal target), and data processing noise. Lawrence Berkeley Laboratory, under DOE/DGE funding, is developing a magnetotelluric method which virtually eliminates the effects of power line noise and instrument noise (Goubau et al., 1978). This approach, and others, need to be investigated for applicability to resistivity, induced polarization, and electromagnetic surveys. Additionally, means need to be obtained for delineating and removing all deleterious noise types from both active and passive electrical methods. Without progress in this direction the ability to obtain reliable interpretations for depths greater than 0.5 km in a geothermal environment may not be possible.

6.2.2.3 Data Interpretation

6.2.2.3.1 Coupled Flow

A most serious limitation of the heat flow method in geothermal exploration lies in the effects of fluid flow. This includes uncertainties about a) lateral transport distances, b) cold water infiltration in recharge areas, c) lateral and vertical flow over long distances of fluids heated by a normal or slightly above normal geothermal gradient, and d) geothermal gradient reversals due to intermixed hot and cold water inflows to a temperature gradient well. This problem is related to a) conductive heat transfer, and its limitations, b) heat and mass

transfer, c) the chemistry and isotopic composition of the transported fluids, and d) the origin of self-potential anomalies. Thus the problem readily generalizes to one of studying flow coupling in convective hydrothermal systems.

6.2.2.3.2 Geochemical detection of deep or blind parts of convective hydrothermal systems

Despite nearly 30 years of geothermal exploration in the United States, our conceptual models of geothermal systems are still crude and naive -- we are hunting elephants with only a vague knowledge of elephant characteristics and behavior patterns. Furthermore, many exploration techniques presently in use simply locate and evaluate near-surface leakage (past or present) from geothermal systems, but may miss deeper blind parts of a geothermal reservoir, parts possibly of dominant importance as an energy source. Improvement of geothermal models and development of new techniques go hand-in-hand, and require thorough study of solid core and fluid samples collected at the surface and acquired during geothermal drilling. Characterization of these materials provides essential information that feeds back into realistic models and thus into more rapid and cost-effective exploration technology.

Presently used geochemical surveys are of two types: (1) chemistry and isotopic composition of springs, fumaroles, or shallow drill holes in which more or less altered samples of the reservoir fluid reach the surface, and (2) surveys of volatile or fugitive constituents (eg., Hg, He, Tl) that have entered soils or rocks surrounding the reservoir. From fluid samples one can infer many aspects of the reservoir fluid, including type

(hot water or steam), temperature, gas content, and subsurface fluid homogeneity. Where large numbers of vents exist, the system size, subsurface structure, and directions of fluid flow may also be indicated. Trace volatiles in solids may also indicate system size and fluid flow even in the absence of hot springs and fumaroles.

These methods are critically dependent on calibration through knowledge of subsurface conditions. Measurements of temperature and salinity variations during and after drilling, collections of aquifer fluids during production tests and with downhole samplers, and squeezing of fluids from core samples provide essential information to relate surface geochemical observations to the nature of reservoir fluids. Ultimately, quantitative mass/heat transfer models--incorporating fluid chemistry, alteration mineralogy, and paragenetic boundary constraints derived from thorough study of core and fluids--will be required to define the chemical processes which relate reservoir fluids to surface geochemical observations.

Refinement or development of new geochemical techniques that might be used to aid location of deep or blind parts of reservoirs is an important goal. This might be accomplished, for example, through documentation of trace element zoning recorded in vein materials deposited by thermal fluids throughout the history of a geothermal system. In addition, known geochemical techniques, such as distribution of trace elements in soils, should be adapted and evaluated for specific geothermal applications. This task must be coordinated with activities in the Geothermal Reservoir Engineering and Geochemical Engineering Programs.

6.2.2.3.3 Two- and Three-dimensional Electrical Model Analysis

Electrical techniques are used routinely for geothermal exploration and evaluation, but we still do not understand the applications and limitations of the various methods in the typically complex geothermal environment. Nor are we able to interpret data properly. Inappropriate one-dimensional (1D) and two-dimensional (2D) interpretation models are used, because the necessary three-dimensional (3D) models are not available or are too expensive. The simple 1D and 2D interpretation algorithms are useful for electromagnetic (EM) and magnetotelluric (MT) exploration in large sedimentary basins, where 1D and 2D models are valid. However, the results can be quite misleading in typical geothermal exploration for convective hydrothermal resources where the earth is typically three-dimensional. Hence, one of the highest research priorities, identified at numerous workshops, is to develop 3D modeling for solutions for survey design, technique comparison, and data interpretation.

6.2.2.3.4 Multiple Geophysical Data Set Analysis

Interpretation of a given geophysical anomaly is a non-unique process and is usually made in terms of one or more preferred earth models out of whole distributions of models that would indeed satisfy the observed data. Hence the preferred model is described by its parameters such as depth, depth extent, width, length, dip, and physical property distributions. More recently it has been recognized that a much better way to express the uncertainty of the model is to state both the

preferred model parameters and parameter confidence intervals based on statistical analysis. The statistical uncertainty of the model is thereby illuminated.

In some cases, one can reduce the statistical uncertainty by interpreting several data sets simultaneously (eg. gravity, magnetics, and seismic, or AMT/MT and resistivity). The improvement in model resolution can be significant. Beyond this, one can fold in constraints on model parameters based on surface geology and geochemistry and on well information including well logs.

The industrial program manager, were he provided with this input, could assess the range of earth models which would fit all data sets, know that this was the narrowest range, and assess the risk of a well missing the target. Clearly the payoff in reduction of exploration costs is large.

Hence a procurement is required which will lead to rapid near-term improvement in our ability to model multiple geophysical data sets with appropriate geological, geochemical, and subsurface constraints.

6.2.2.3.5 Geothermal Earth System Models

Geothermal exploration consists of measuring geological, geochemical, geophysical, and hydrological data at the earth's surface and/or above and below it, and interpreting them in terms of the parameters of a model of the geothermal system.

Models of geothermal systems, as used in geothermal exploration, must be segregated with respect to scale and type of resource. Once this segregation has been made, the development of a conceptual model of the system begins. As more and more data are acquired, the conceptual model

moves closer to a true model of the subsurface. Each stage in development of the conceptual model requires additional numerical modeling of the available geophysical data sets, often via multiple data set modeling, using appropriate geological, geochemical, hydrological, and well-bore knowledge constraints. The collection of every piece of additional data required to refine the conceptual model will be controlled by benefit/cost analysis.

The earth models so developed provide targets for exploratory and step-out drilling. Ideally, the models move closer to the real earth with every well drilled.

Research is required which will lead to near-term rapid advancement of our abilities to develop conceptual models of each subset of the convective hydrothermal resource type. If successful, the result of this RD & D effort will be a marked reduction in expenditures associated with dry holes and a marked improvement in the confidence of utilities in geothermal resources. Further, by sensitivity analyses, developers and utilities will both gain better appreciation for the uncertainties and hence risks associated with predicting reservoir performance.

Assessment of the importance of each set of geoscience data to defining the model is the immediate object of this task. Ultimately, this assessment should lead to a basis for developing optimum exploration strategies. This task is fed by the results of all earlier tasks. Work under this task will be coordinated with other related ongoing federal programs, especially with the Reservoir Engineering program.

6.2.3 Exploration Strategies

It is well known that major differences exist between the exploration strategies used by different industrial geothermal exploration companies. Illumination on optimum strategies or optimum ranges of strategies used to search for convective hydrothermal systems has received attention during recent years as Ward (1977) and Goldstein et al. (1978) have reported. A relatively small effort is required to advance further these studies and to introduce mathematical and statistical quantification of them. A significant reduction in the cost of geothermal exploration will result from this effort.

6.2.4 Technology Transfer

Some industrial geothermal developers are totally conversant with state-of-the-art technology in geothermal exploration; many are not. The reasons for slowness of assimilation of technology to industry from RD & D professionals arises in many ways including a) disinterest by or inability of universities, government agencies, or contractors to transfer technology, b) lack of assimilators of technology in industry, or c) lack of a government program designed to eliminate the institutional, legal, and economic barriers to technology transfer. Herein we propose a major effort to remove all three barriers to technology transfer.

Workshops, short courses, seminars, demonstrations, reference manuals, study of barrier structures, and dissemination of computer listings of geothermal exploration algorithms are all part of an outreach program which will be lead by UU/UURI, assisted by UC/LBL, but for which a small effort in specific procurements elsewhere will be an integral part of the program.

6.3 Task Descriptions, Mid- and Far-Term

The activities under this subsection are far reaching but not yet defined well. Accordingly, it would be premature to attempt to expand upon them in this initial Program Plan. However, the Plan calls for early delineation of them. The stress in the near-term is on high-temperature convective hydrothermal resources. In the mid- and far-term the stress is expected to shift to one or more of the other resource types, i.e. intermediate-to low-temperature convective hydrothermal, geopressured, hot dry rock, magma, radiogenic, and normal geothermal gradient resources. Table 5-4 spells out the objectives for the mid- and far-term while Table 6-2 spells out the tasks to be associated with these objectives.

APPENDIX 6PRELIMINARY IDENTIFICATION OF BASIC
GEOSCIENCE RESEARCH REQUIRED TO SUPPORT GEOTHERMAL EXPLORATION1.0 Regional Crustal Studies1.1 Problem and Objective

1. The objective is to obtain a basic understanding of the genesis, development and geometry of each of the potential sites listed below.

1.2 Methods

Use aeromagnetic, gravity, MT/AMT, geologic mapping, reflection and refraction seismic, heat flow, hydrology, chemistry, and isotopes, age dating, and drilling, plus detailed simultaneous interpretation thereof, to examine the nature and extent of these features from the surface to upper mantle depths.

1.3 Potential Sites

1. Rio Grande rift in NM and CO
2. Pioche-Beaver-Tushar trend in UT and NV
3. Battle Mountain heat flow high in NV
4. Madison aquifer in ND, SD, MT, WY
5. Radiogenic plutons throughout the U.S.
6. Upwarps of geotherms in the U.S.
7. Snake River plain in ID
8. Wasatch front in UT

9. Young volcanic centers in the U.S.
10. Existing magmas in the U.S.

1.4 Justification

Each potential site contains known warm to hot geothermal fluids and potential sites for hot dry rock, magma, radiogenic, and normal geothermal gradient resource types.

2.0 Deep Circulation in Crustal Fractures

2.1 Problem and Objective

The manner in which meteoric waters descend to be heated by normal and abnormal geothermal gradients, the depths to which these waters descend, the transport mechanisms and geometries accompanying the descent and ascent, the energy flow couplings involved, and the volume of fluid in motion at any one time are all unknowns in convective hydrothermal systems. The objective is to provide an understanding of these facets of deep circulation in crustal fractures.

2.2 Methods

1. Study and model the hydrology, heat and mass transfer, chemistry and isotopic composition of flow in fractured crustal materials to depths of 5km.
2. Map several fracture systems via geology, stress state, seismic fault plane solutions, electrical resistivity, radioactive tracers, and other means.

2.3 Potential Sites

1. Margins of the Snake River plain in ID
2. Margins of Rio Grande Rift in NM and CO
3. Wasatch front in UT
4. Active fault zones in AK, CA, OR, WA, HI.

2.4 Justification

This work is fundamental to an understanding of all convective hydrothermal systems and of the origin of the many hot spring resources in the Western U.S.

3.0 Generation and Evolution of Silicic Magma Systems

3.1 Problem and Objectives

The problem is to establish the manner in which silicic magmatic systems are formed and how they evolve. Of critical importance is the determination of the thermal life spans of volcanic centers as well as the conditions/formations of magmas, magma transfer in the crust, the evolution of volcanic systems, magma chambers, and their associated geothermal systems. Thermal modeling of volcanic systems requires an adequate understanding of magma fluid mechanics including conditions for convection and the nature of the flow regime in the magma chamber. The study of fossil volcanic systems would provide additional data for the interpretation and modeling of younger thermally active systems.

3.2 Method

Conduct geological, geochemical, and geophysical studies of Tertiary and Quaternary silicic volcanic centers in the western United States. The data to be obtained include geologic mapping, detailed petrology, ages of volcanism, full spectrum chemical analyses, isotopic analyses, structural analyses and applicable geophysical data.

3.3 Potential Sites

1. Cove Creek domes, UT
2. Snake River Plain rhyolites, ID
3. Blackfoot Reservoir rhyolites, ID
4. Thomas Range rhyolites, UT

5. Marysvale caldera, UT

3.4 Justification

There is a direct relationship between young silicic volcanism and established high temperature convective hydrothermal resources. A similar relationship can be expected between young silicic volcanism and hot dry rock resources. In some instances, the young silicic volcanic rocks may exist as melts or partial melts which would be still another resource type.

4.0 Basic Research in Electrical/Electromagnetic Modeling

4.1 Problem and Objective

The ability to interpret the results of electrical and electromagnetic measurements is limited by the range of models for which there are known solutions. At the present time many of the electrical and electromagnetic methods have satisfactory models (mostly numerical) for 2 dimensions with complicated geometry and partly satisfactory models for 3 dimensions with simple geometry. However, experience has shown that interpretation of electrical surveys usually should be treated as rather complicated 3 dimensional cases. Also, as hardware and interpretational techniques have improved, there has grown a desire to explore for targets that have a more subtle signature (signal) in the sense that they are deeper and/or have smaller contrasts in properties. Smaller signatures (signal) coupled with the 3 dimensional complexity of the real geological environment (noise) leads to a rather severe signal-to-noise ratio problem.

Basic research in modeling techniques, both numerical and scale modeling, is needed to overcome these problems and to provide modeling at reasonable cost.

The objective is to improve the ability to interpret electrical and electromagnetic data in complicated geological environments where the signal-to-noise ratio is low.

4.2 Method

Develop modeling capability, including analytical, numerical and

scaled physical, so that geometrically complex models can be solved in a cost-effective manner.

4.3 Justification

Intelligent application of electrical methods in geothermal exploration and in supporting crustal studies is seriously hampered by a limited ability to interpret data from electrical surveys.

5.0 Basic Research on Rock Properties

5.1 Problem and Objective

The various geophysical measurements (surface or borehole) yield through the interpretation process some knowledge of the geometrical distribution of a particular rock property, such as electrical conductivity, seismic velocity, density, temperature, or others. Although the distribution of one or most of these properties and their values may be the objective of the geophysical measurement, often the desired information is related in some complicated way to the measured property. For example, in the geothermal environment the desired information might be the distribution of temperature, porosity, permeability, and pore fluid salinity, while the measured quantities might be some of those mentioned above. In the case of the electrical conductivity, we know that conductivity depends on temperature, porosity, and salinity and we cannot determine all of these uniquely from a single measurement. However, other rock properties such as seismic velocity also depend on at least temperature and porosity, so that combinations of geophysical measurements with geological constraints could provide information on parameters of more direct interest. Our present understanding of rock properties and their dependence on various parameters is limited, especially under the conditions that exist in geothermal areas.

What is needed is a body of experimental data on rock properties under conditions that simulate those in the various types of geothermal environments. These data can then be used to develop models that relate a

particular rock property (conductivity, velocity) to the various parameters (temperature, porosity, pressure) which we desire to determine.

The objective is to develop an understanding (model) of the dependence of measured rock properties on the more fundamental parameters of the rock. These models can then be used to predict a particular rock property given the various parameters, and also, in the inverse sense, they can be used to predict the parameters given the measurements of the appropriate properties.

5.2 Program

Develop a laboratory program to measure geophysical rock properties under conditions that simulate those in the several types of geothermal environments. These basic data should be used to develop models that relate the rock properties to the controlled parameters.

5.3 Justification

The data to be collected is fundamental to understanding geoscientific data used to detect and delineate the several geothermal resource types.

6.0 Deep Drilling to the Source of a High-Temperature Convective Hydrothermal System

6.1 Problem and Objective

The objective is to obtain a basic understanding of the source of heat, heat and mass transfer mechanisms, age and other parameters at the heart of a high-temperature convective hydrothermal system.

6.2 Method

Drill to depths of 5 to 10 km in the heart of a hydrothermal system, and perform geological, geophysical and geochemical studies on the retrieved samples and in drill logs.

6.3 Potential Sites

1. Valles Caldera, NM
2. The Geysers, CA
3. Roosevelt Hot Springs, UT
4. Humboldt House, NV
5. Soda Lake/Stillwater, NV
6. Desert Peak, NV
7. Heber, CA
8. East Mesa, CA

6.4 Justification

Basic geologic controls on hydrothermal and perhaps other geothermal resource types are expected to be identified.

7.0 Complete Geologic, Gravity, and Aeromagnetic Coverage of Western U.S. and East Coast U.S.

7.1 Objective

To map, and therefore acquire a basic understanding of, broad regions in which geothermal resources might be developed.

7.2 Method

Intermediate-scale coverage would be obtained by systematic geologic, gravity and aeromagnetic surveys on a scale of 1:250,000 of the high heat flow western U.S. and the potential radiogenic sources in the eastern U.S. This is basically a rapid acceleration of an existing USGS program but which will need additional financing via DOE. Coordination with NURE and with the USGS mineral resource assessment program would be essential.

7.3 Potential Sites

1. The U.S. west of the Rocky Mountains.
2. The U.S. east coast belt of radiogenic heat sources buried beneath blankets of thermally insulating sediments.

7.4 Justification

The most fundamental geoscience input to detecting, delineating, and assessing geothermal resources in two key regions is largely lacking. This basic study is essential not only to geothermal exploration, but to crustal studies and mineral exploration.

8.0 Fundamental Study of Crustal Processes which are Characteristic of Geothermal Regions

8.1 Objectives

To stimulate basic thinking of crustal processes particularly as they lead to the production, transfer, and accumulation of heat and to develop an understanding of the genesis and location of each type of currently known geothermal resource for the purpose of predicting occurrences of yet to be defined resources.

8.2 Methods

All geoscientific methods

8.3 Potential Sites

The globe

8.4 Justification

New concepts of geothermal resources and of their genesis need to be developed now in order to provide exploration methods for mid- and far-term resources.

9.0 Theoretical and Laboratory Studies of Reactions between Magmas and Country Rocks

9.1 Objectives

To provide a theoretical and experimental framework for water/rock interactions.

9.2 Methods

All geoscientific methods

9.3 Potential Sites

Not applicable

9.4 Justification

One of the weakest links in understanding the genesis, history, and currently operating mechanisms of a convective hydrothermal system and a hot dry rock system, and means for their detection and delineation, is the theoretical basis of their existence.

10.0 Theoretical and Laboratory Studies of Hydrothermal Aqueous Solutions

10.1 Objective

To provide a theoretical and experimental understanding of the physical chemistry and chemical structure of hydrothermal fluids, of their interaction with rock materials of the earth's crust, of their genesis and chemical evolution in crustal environments of various types, and of their movement in the crust.

10.2 Methods

All pertinent geoscientific methods.

10.3 Potential Sites

NA

10.4 Justification

Hydrothermal aqueous fluids are the actual medium by which the heat of geothermal resources is transferred to the earth's surface. Understanding their nature is fundamental to any existing or potential geothermal resource.

11.0 Defining the Global Distribution of Geothermal Gradients

11.1 Objective

Define the "normal" geothermal gradient, its variability, and its correlation with physiographic units to depths of 10 km.

11.2 Methods

All pertinent geoscientific methods with emphasis on gradient and heat flow measurements, rate of radiogenic heat generation in the crust, and mantle heat flow.

11.3 Potential Sites

Emphasis on measurements in the U.S. with collection and interpretation of data from the rest of the world.

11.4 Justification

If we are to utilize the normal geothermal gradient as a geothermal resource we must understand all its variations better.

12.0 Research on the Development of Geopressed Geothermal Resources

12.1 Objective

To understand the fundamental processes leading to the development of geopressed geothermal resources.

12.2 Methods

All pertinent geoscientific methods

12.3 Potential Sites

The Gulf Coast of the U.S.

Other selected sedimentary basins in the U.S.

12.4 Justification

To discover and exploit a resource, we need to understand its genesis.

13.0 Research on the Development of Radiogenic Heat Sources

13.1 Objective

To understand the fundamental processes and boundary conditions leading to the development of a radiogenic geothermal resource.

13.2 Methods

All pertinent geoscientific methods

13.3 Potential Sites

Throughout the world.

13.4 Justification

To discover and exploit a resource, we need to understand its genesis.

14.0 Define Stress Distribution Mechanisms in the Crust to 3 Km

14.1 Objectives

To obtain a description of the ranges of three-dimensional tri-axial stress distributions in selected regions in the crust.

14.2 Methods

1. Structural Geology
2. Mechanics of Inhomogeneous Fractured Materials

14.3 Potential Sites

1. The Geysers
2. Wairakei
3. Roosevelt Hot Springs
4. Coso Hot Springs
5. Humboldt House
6. Cerro Prieto

14.4 Justification

Fracture-dominated convective hydrothermal systems are poorly understood at best. Their understanding is fundamental to estimating their size, productivity, temperature, pressure, and longevity.

APPENDIX 7

TECHNICAL REVIEW COMMITTEES

The following technical review committees will be used to recommend specific technology development and research for federal funding.

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APPENDIX 8

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