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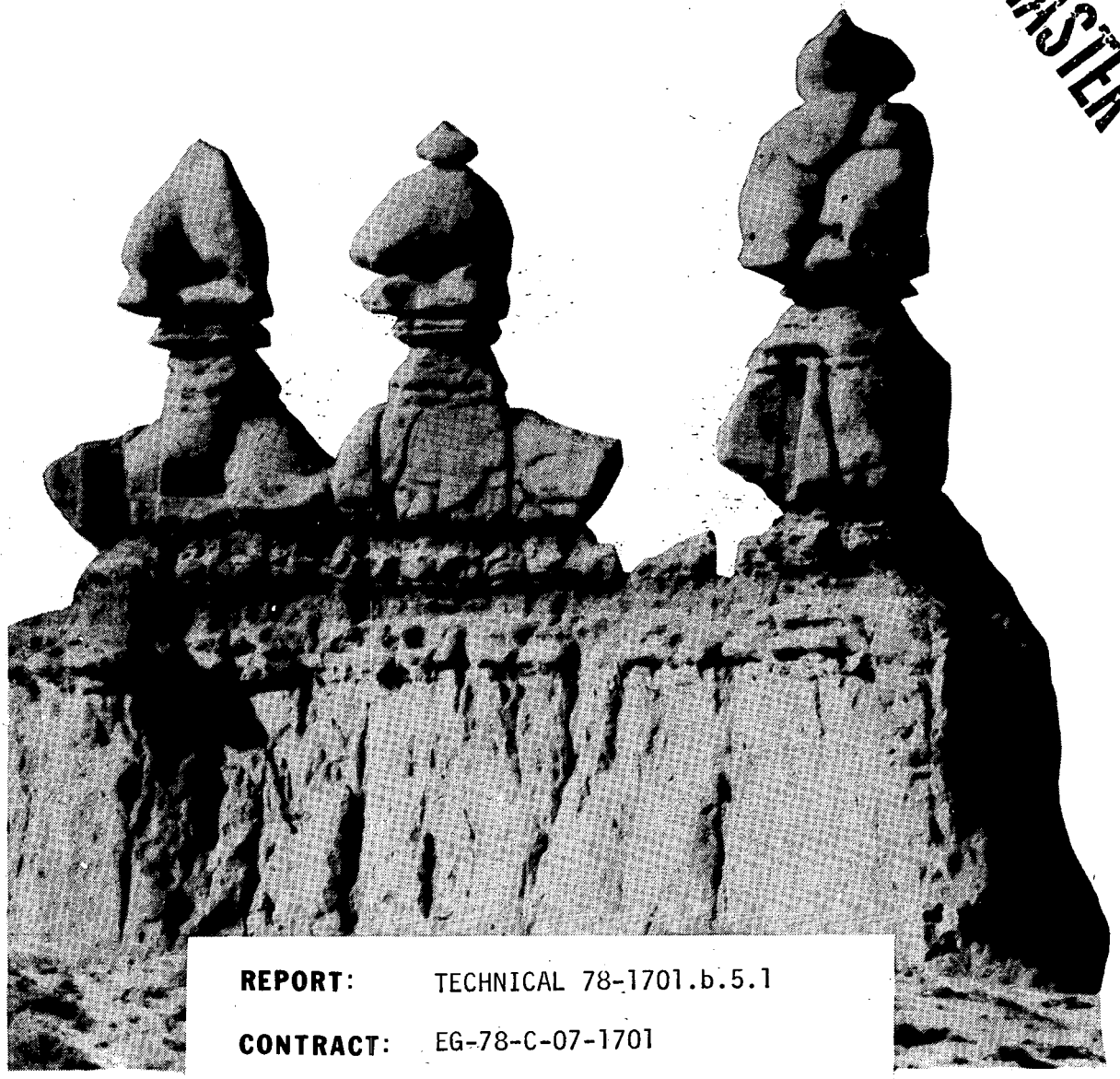

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Program Review

Resource Evaluation, Reservoir Confirmation, and Exploration Technology

Division of Geothermal Energy

Department of Energy

(DOE/DGE)

by

Stanley H. Ward

University of Utah

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Program Review

Resource Evaluation, Reservoir Confirmation,

and Exploration Technology

Division of Geothermal Energy

Department of Energy

(DOE/DGE)

1.0 Introduction

In order to seek to match the DOE/DGE proposed programs with the needs of the nation, the states and industry and to meet the national goals set forth in Table 1, the University of Utah has assisted DOE/DGE in a review of its programs in resource evaluation, reservoir confirmation, and exploration technology.

To effect this review, seven consortia of specialists were identified as in Appendix 1. These consortia met and discussed the specialists viewpoints on the specific needs for DOE/DGE support to ensure reaching the national goals. Their reports are set forth verbatim in section 4.0.

Additionally, 28 managers of industrial geothermal exploration programs were contacted to obtain their opinions. Appendix 2 lists those contacted. The comments received constitute Appendix 3.

Finally, a Program Review Panel Meeting, with the participants of Appendix 4, was held in Salt Lake City, Utah, on March 8, 1978 to review all inputs received to that date and to recommend a program of geothermal resource evaluation, reservoir confirmation, and exploration technology to

DOE/DGE. The next section contains a summary of the recommendations so obtained.

As a means of stimulating discussion, a document, describing a tentative (or straw-man) strategy for Resource Evaluation Reservoir Confirmation & Exploration Technology, was distributed to 28 managers of geothermal exploration programs and to each of the members of the seven technical consortia. This document and its covering letter appear as Appendix 5.

This report intends to convey the details of the program review as well as to provide a summary of the recommendations, means for their implementation, and a six year program of expenditures which would accomplish the objectives of the recommendations. The summary of recommendations, plans for implementation, and plan of expenditures is the sole work of the author but is based on the input of all others involved in the review process. This document is intended as a guide to program managers as they develop specific program planning documents.

TABLE 1

DOE GOALS FOR GEOTHERMAL RESOURCES

A. Electric Power Generation

1985	3,000 - 4,000 MWe	0.1 to 0.2 Quads/Yr
2000	20,000 - 40,000 MWe	0.5 to 2.0 Quads/Yr
2020	70,000 - 140,000 MWe	6.0 to 8.0 Quads/Yr

B. Direct Heat

1985	0.2 to 0.3 Quads/Yr
2000	1.5 to 3.5 Quads/Yr
2020	5.0 to 10.0 Quads/Yr

1 Quad = 10^{15} BTU ~ 170 million barrels of oil
~38 million tons of coal

1000 MWe ~ one nuclear power plant ~ 1 million people

2.0 Summary of Recommendations

Because of a reorganization of DOE/DGE programs, we shall discuss exploration technology separately from resource evaluation and reservoir confirmation. The latter two categories of activities are divided into a Geopressured-Eastern region under B. de Bono, a Rocky Mountain-Great Basin region under J. W. Salisbury, and a Pacific States region under R. Toms. The following recommendations are not so divided for we leave this task to the regional managers. I have exercised minimal editorial prerogative in assembling these recommendations.

The symbols N (near-term), M (mid-term), and F (far-term) are inserted where appropriate; they refer to items which will contribute to new heat or new power on line by 1985 (N), items which will impact heat or power on line by 1990 (M), and items which will impact heat or power on line at later times. I have presented recommended budgets through 1984; these are my own best estimates based on all data available to me. Clearly, they stress near-term objectives.

2.1 Resource Evaluation & Reservoir Assessment

2.1.1 Thermal Methods

2.1.1.1 (N) Regional Thermal Measurements, Free Hole.
A systematic and extensive program of making temperature measurements in available drill holes should be implemented as soon as possible and at a relatively high level of funding. Coordination with the NURE program of DOE should

be sought.

2.1.1.2 (N,M,F) Regional Shallow Drilling

A systematic drilling program should be implemented as soon as possible. This drilling should include one hundred to five hundred holes per year, to depths of 100 to 150 m, spaced in such a way as to fill in the gaps in the "free hole" data of 1) above and to investigate specific provinces and problems. These holes should not be drilled in order to delineate specific geothermal reservoirs, however. Again, coordination with the NURE program should be sought.

2.1.1.3 (N) Drill and/or preserve deep holes.

Of interest here are holes in the 600-1000m range which are routinely drilled for mineral exploration, water, and petroleum exploration. These holes, where non-productive, are cemented and abandoned. Accordingly, it is recommended that DOE/DGE assume responsibility for these holes prior to plugging. Casing would need to be set to prevent hole collapse in many instances.

Additionally, and in conjunction with this program ten holes per year should be drilled and logged to 1000m.

2.1.1.4 (N) Collate Data

All data collected under 2.1.1.1 through 2.1.1.3 above should be collated with existing data, local and regional maps prepared, and crustal models developed.

2.1.2 (N,M,F) Water/Rock Interaction

In drilling oil and gas wells, well logs are used and are adequate for delineating producing zones. However, well logs are not adequate for delineating producing zones in fracture-dominated geothermal reservoirs. Entry and exit of hot and cold fluids is not totally described by well logs. To augment logs, we require chemical, mineralogical, and isotopic analyses of cores, cuttings, and fluids. Mineral alteration assemblages, for example, are directly indicative of specific temperature-pressure regimes while isotopic analyses of fluids and rocks are indicative of maximum temperatures at specific entry points for fluids.

Industry is not equipped, in general, to make the decisions on sampling procedures, analytic procedures, interpretative procedures, and the placing of well casing for this problem, yet no well should be drilled without a comprehensive plan for core, cuttings, and fluids utilization and for specific and alternate well casing emplacement. Commercial contractors are not yet available to provide these full spectrum geochemical services. Accordingly, it is incumbent upon DOE/DGE to finance these activities, totally, wherever it provides matching funds under the Industry-Coupled or State-Coupled programs.

As time progresses, we anticipate refinement of techniques so that DOE/DGE should continue to lead the field in this area of activity if it is to enhance heat or power on line in the near-,

mid-, and far-term.

Table 2 contains a summary of near-term, mid-term, and far-term objectives with strategies for achieving them.

DOE/DGE funded geothermal wells are being drilled or are planned at a number of locations under the State-coupled and Industry-coupled programs of DOE/DGE. It is important that a systematic program of sample acquisition, storage, distribution, and study be set up immediately so that maximum benefit can be realized from the unusual opportunities presented by these expensive wells. DOE support and funding should be provided in the following areas: 1) sample acquisition, 2) sample curation, preparation, and distribution to researchers, 3) generation of basic background data, and 4) detailed characterization and study of samples.

All regional and reservoir investigations supported by DOE/DGE should have appropriate components dealing with sampling and study of rocks and fluids from geothermal wells and from the earth's surface. Rocks and fluids are normally sampled and analyzed separately, but interpretation of results requires integration of both data sets, along with supplementary borehole logs and geological information.

Fluid and rock samples present different kinds of problems and opportunities, which require separate consideration. A fluid sample at the well-head is a mixture derived from the whole

TABLE 2

RECOMMENDATIONS

Recommended Item	Desired End Product(s)		Strategy	
	Regional	Reservoir	Regional	Reservoir
1. Assessment of past and current studies of rocks/ fluids (N)	a) Specify and publish present understanding of regional data for use in new interpretation of reservoir data b) Identify gaps	a) Specify and publish present understanding of utility of water/ rock data to exploration and evaluation b) Identify gaps	Invited participant workshop with published proceedings	
2. Surface rock and fluid sampling program (N)	Broad-spaced samples of fresh and altered rock, vein fracture, fault material and waters in regional areas around certain geothermal areas	Detailed samples of fresh and altered rock, vein, fracture and fault material and surface and shallow water in geothermal areas of interest	Fund sampling programs	
3. Sampling of geothermal wells (N)	Drill hole samples in areas around geothermal areas of interest	Complete suite of drill hole samples (fluid and rock) in geothermal areas of interest	Drill intermediate-depth holes for sample acquisition	Actively seek to acquire samples from DOE and other geothermal wel as they are drilled
4. Acquisition of samples from existing wells drilled for oil, minerals, water, geothermal (N,M,F)	Samples from wells-of-opportunity which meet criteria of usefulness to geothermal research		Obtain samples from American Stratigraphic, state geological surveys, past geothermal projects	
5. Analysis of rock and fluid (ET) samples (M,F)	Specification of geochemical, mineralogical, and geophysical parameters of interest in geothermal research		Fund appropriately received researc proposals	
6. Synthesis of studies (M,F) (ET)	Better understanding of regional data for use in improved interpretation of reservoir data	Water/rock models of geothermal systems	Periodic invited-participant workshops with published proceedings	
7. Geothermal sample library (N)	Availability to researchers of appropriately curated samples of rocks and fluids from geothermal areas		Fund at UURI	

production interval, which has been fractioned into noncondensible gas, steam and water phases in transit up the borehole to the sample bottle. Rock samples are much more heterogeneous and so require more detailed studies. Both types of samples are subject to contamination by drilling muds and fluids. Funding levels should recognize these problems.

2.1.3 Electrical Methods

The application of electrical methods in the geothermal environment is poorly understood, yet they are of fundamental importance in spotting the locations of wells in fractured and altered ground. Accordingly, DOE/DGE should encourage via the State-Coupled and Industry-Coupled programs the following.

2.1.3.1 (N) Case Histories

Dissemination of case histories and information on theoretical and field studies of reconnaissance and detailed electrical methods.

2.1.3.2 (N) Comparative Studies

Establish relative cost-effectiveness, resolution, advantages, limitations, and a place within exploration architecture for the various electrical methods.

2.1.3.3 (M,F) Regional Electrical Data Base

If exploration technology warrants it, establish a regional

electrical data base.

2.1.4 Seismic Methods

High resolution seismic reflection methods have appeared on the market only in the last several years. They are adaptations of petroleum seismic methods to mining exploration, civil engineering, and more recently to geothermal exploration. Because they are so expensive, they are used in geothermal exploration only after the first successful well has been drilled on a prospect. Those companies that can afford to use high resolution seismic reflection are doing so in a strictly proprietary manner for fault and fracture delineation. The advantages, limitations, problems, and needed improvements are not known to the industry at large. Yet the method is potentially the most powerful means of reducing misplaced wells and, therefore, the most viable means of effecting significant cost reduction in developing a geothermal field.

2.1.4.1 (N) Data Acquisition & Interpretation, Areas Previously Drilled

As the top priority under this topic, DOE/DGE should purchase, via the Industry-Coupled Program, high resolution seismic reflection survey data obtained across geothermal reservoirs. Funds should be made available to reprocess the data, and to study means of reducing the costs of high-resolution seismic surveys.

2.1.4.2 (N,M,F) Environmental Monitoring

Microearthquake monitoring should be funded by DOE/DGE as environmental baseline studies of and/or as contributions to recognize induced from natural earthquakes at all geothermal prospects at which electric power generation or heat production seems probable.

2.1.5 Reservoir Modeling

2.1.5.1 (N) World-Wide Inventory

A world-wide inventory of geothermal fields should be made to establish the basic convective hydrothermal conceptual models, upon which all expensive drilling must rely.

2.1.5.2 (N,M,F) Site Specific Application, Exploration Technology

Site specific models should be developed of rift system, subduction system, extension system, and buried pluton models under the Industry-Coupled, State-Coupled, and Pre-Commercial Programs in order to assist in minimizing drilling costs.

2.1.6 Rock Properties

2.1.6.1 (N,M,F) Measurements

Via the Industry-Coupled and State-Coupled programs, establish a systematic program of measurement of rock properties on surface samples, drill cuttings, and cores.

The specific properties and their relationships are to be established under exploration technology.

If we know more about the chemical and physical properties of cores and cuttings, we will accelerate near-term reservoir development by placing exploratory wells in optimum locations and thereby reducing the number of dry holes. Further, we will understand the host rocks better and therefore contribute to design of hydrofracturing which again will accelerate more power on line in the near-term. Finally, we shall provide control information on subsidence which in turn may be an institutional deterent to full development of a given geothermal field.

To facilitate this activity, local centers for storage, curation, and analysis of cores, cuttings, and surface samples are required.

2.1.6.2 (N) Coring

Via the Industry-Coupled program, support the cost of coring in industry-financed wells. Industry does not have nor can it readily acquire the expertise needed to make critical path decisions which must be based on the specialized studies of 2.2.6 below.

Tables 3, 4, and 5 list the rock properties which require measurement.

2.1.7 (N) Igneous Processes

TABLE 3

REQUIRED CAP AND RESERVOIR ROCK PROPERTIES
FOR GEOTHERMAL EXPLORATION

Rock Property	Priority
(i) Heat Flow	
Thermal Conductivity	1
Effective Porosity	1
Permeability	1
(ii) Electrical Resistivity	
Electrical Conductivity	1
Density (Bulk and Grain)	1
Streaming Potential Coefficient	2
Thermoelectric Potential	3
Other Cross-coupling Coefficients	3
Zeta Potential	3
(iii) Magnetic	
Magnetic Susceptibility	1
Density (Bulk and Grain)	1
Curie Temperature	2
(iv) Gravity	
Density (Bulk and Grain)	1
(v) Seismic	
Wave Velocities (V_p and V_s)	1
Density (Bulk)	1
Attenuation	2

Parameters

Pressures (Overburden, Confining and Pore Pressures)
Pore Fluid
Temperature
Core Variability
Electrical Current Density } Limited to Electrical Conductivity
Applied Current Frequency } Limited to Electrical Conductivity

TABLE 4

REQUIRED CAP AND RESERVOIR ROCK PROPERTIES
FOR GEOTHERMAL EXPLORATION

Rock Property	Priority
Porosity	1
Permeability	1
Resistivity	1
Neutron Absorption	2
Electron Density	2

Parameters

Pressures (Overburden, Confining and Pore Pressure)
Reservoir Fluid
Temperature
Core Variability

TABLE 5

REQUIRED CAP AND RESERVOIR PROPERTIES FOR
ENVIRONMENTAL STUDIES AND
RESERVOIR ENGINEERING

Rock Property	Priority
Density (Bulk, Grain and Dry)	1
Effective Porosity	1
Mineralogy	1
Permeability and Relative Permeability (Matrix/Fracture)	1
Specific Heat	2
Thermal Conductivity	2
Grain Size Distribution	3
Thermal Expansion	3
Elastic Moduli, including Poisson's Ratio	3
Rock Strength, including fracture mode	3
Coefficient of Sliding Friction	3
Long Term Nonlinear Stress-Strain Relations	3

Parameters

- Pressures (Overburden, Confining and Pore Pressure)
- Reservoir Fluid
- Temperature
- Time
- Core Variability

In conjunction with the Industry-Coupled and the State-Coupled Programs there is a need to provide for identifying, classifying, and dating young recent volcanic and intrusive rocks, in a site-specific sense. Further, there is a need to ensure utilization, assimilation, and dissemination of igneous data. The U.S.G.S. program paralleling this identifies with mid-term and far-term goals. DOE/DGE should only be concerned with near-term goals in this activity. The capability for predicting, in the near-term, the heat capacity of a reservoir clearly exists in this item.

2.2 Exploration Technology

2.2.1 (N) Thermal Methods

One basic objective in this technical category is to facilitate an expanded program of precision temperature, geothermal gradient, thermal conductivity, and heat flow measurement. Accordingly, the specific objectives are:

2.2.1.1 Portable Temperature Logging Gear

Develop less expensive yet precise and portable logging equipment than is currently available.

[Inexpensive, off-the-shelf precision (0.01°C) equipment is not commercially available but yet will be needed for the expanded program of thermal measurements recommended under resource evaluation and reservoir assessment.]

2.2.1.2 In Situ Thermal Conductivity

Develop reliable inexpensive in-situ methods for measurement of such parameters as thermal conductivity, thermal diffusivity, porosity, and fluid flow.

[At present cores or chips must be brought back to the laboratory for measurement of thermal conductivity. A more cost-effective approach would be to measure heat flow directly in the field via in-situ thermal conductivity, thermal diffusivity, and porosity measurements. Additionally, we need to measure fluid flow directly in drill holes in order to correct for the effects of this flow].

2.2.1.3 Laboratory Thermal Conductivity

If 2.2.1.2 above cannot be achieved then methods must be developed for rapid and inexpensive conductivity measurements in the laboratory. Again both 2.2.1.2 and 2.2.1.3 are directed toward reducing the cost of the expanded program of thermal measurements recommended under resource evaluation and reservoir assessment.

2.2.1.4 High Temperature Logging Gear

Adapt existing or improved portable temperature measuring instruments for use at temperatures in excess of 150°C.

[No capability exists to measure such temperatures if they are found in shallow wells].

A second basic objective in this technical category is the study

of the effects of groundwater flow on temperature and heat flow as they relate to geothermal exploration. Accordingly, the specific objectives are:

2.2.1.5 Thermal/Hydrologic Case Histories

Record and distribute case histories which include both thermal and hydrological measurements.

[Many geothermal prospects are partially or completely screened from thermal observation by cold water overflow and cold/hot water mixing. Documentation, distribution and analyses of these data sets are essential if we are to overcome this problem].

2.2.1.6 Theoretical Thermal/Hydrologic Studies

Conduct theoretical studies of combined hydrological/heat flow regimes, i.e., conductive and convective heat transport.

[The reason for this development is the same as for 5) above].

2.2.2 (N,M,F) Water/Rock Interaction

The Water/Rock Interaction consortium summarized its results in tabular form; these recommendations were reproduced above as Table 2. Under Exploration Technology I would place items 5) and 6) of Table 2. Justifications for their pursuit are contained in 2.1.2 above.

2.2.3 Electrical Methods

The utilization of electrical methods is not understood totally in geothermal areas yet industry utilizes these methods routinely. They are of particular importance in mapping faults and fractures and zones of alteration, and are therefore fundamental in the location of wells. So many different methods exist that industry is confused over which method is best and, accordingly, wastes resources in the application of these methods. Industry does not have the manpower and experience necessary to solve its problems in this area. Yet these resources exist within the nation and can be directed to solution of the pertinent problems. Most centers of significance in development of electrical methods for geothermal exploration exists in government or academic laboratories. These laboratories need to be put to use to assist industry and contractors in the near-term. Accordingly the following program is recommended.

2.2.3.1 (N) State of the Art Capabilities

Establish the comparative capabilities of state-of-the-art electromagnetic, resistivity, induced polarization, and AMT/MT methods.

2.2.3.2 (N,M) Methods Used in Consort

Establish the contribution of the several electrical methods when used in consort.

2.2.3.3 (N,M,F) 2D, 3D Interpretation

Establish via numerical analysis or model tank experiments, 2D and 3D interpretational techniques which will permit

comparison of the several techniques and full exploitation of one or more of them.

2.2.3.4 (N) AMT/MT Problems

Identify and remove the noise, instrumental, and interpretational problems of the AMT/MT method at an early date or, alternatively, recommend its abandonment in complex geological environments.

2.2.3.5 (M,F) S.P. Method

Document the utility, or lack thereof, of the S.P. method, in a wide variety of geologic settings using *a priori* evaluation criteria.

2.2.3.6 (M,F) Time and Frequency Domain

Develop a systematic analysis of the relative advantages and disadvantages of time-domain and frequency-domain analyses of active source electromagnetic data.

2.2.4 (N) Seismic Methods

The high resolution seismic reflection method discussed under 2.1.4 above is so expensive that alternate means to provide this information must be sought. The most viable alternative is a combination of seismic refraction and one or more of the passive seismic methods. Some companies have used this approach but with mixed success. What is required is a comprehensive development program wherein seismic refraction, microearthquake and teleseismic P-wave delay surveys would be run

concurrently. Such a package approach does not exist and yet, if it could replace high resolution seismic surveys, would lead to a 50% reduction in seismic costs. Accordingly it is recommended that:

2.2.4.1 Passive Seismic Network

A detailed net of at least 16 digital, high quality, three-component seismographs be operated at each of three different well-documented geothermal prospects to a) map P-wave traveltime and seismic attenuation delays, and b) record microearthquakes. A detailed seismic refraction survey should be run concurrently at each prospect. The cost-effectiveness of this technique should be assessed thereby.

2.2.4.2 Interpretation

Support technology which will improve interpretation and analyses techniques associated with 1) above.

2.2.5 (N,M) Reservoir Modeling

After more than twenty years of geothermal exploration in the United States our conceptual models of geothermal systems are still very crude. Present day exploration technology, to a large extent, identifies and evaluates only near surface leakage from the geothermal system. The identification and evaluation of blind portions of geothermal systems remains a large unknown. Improvement in exploration technology depends upon development of

better geothermal models.

Reservoir modeling uses the results of geological, geochemical, and geophysical studies performed by surface observations, by observations on drill samples of rock and fluid, and by well-bore logging. The output of reservoir modeling is useful in:

1) Helping to predict reservoir productivity, longevity, and size by providing values for important reservoir parameters such as:

a) temperature

b) porosity

c) permeability

d) pressure

e) geometry

f) nature and chemistry of fluid

g) thermal conductivity.

2) Improving both regional and site-specific exploration technology by providing data on:

a) density

b) seismic velocity

c) electrical resistivity

d) total magnetization

e) bulk polarizability

f) expected earthquake locations, magnitude, local mechanism, and recurrence relations

g) expected geochemical dispersion patterns.

The tasks recommended to obtain significant progress in reservoir modeling are:

2.2.5.1 Multiple Data Set Modeling

Fund studies to develop cost effective ways for two- and three-dimensional modeling of magnetotelluric (MT), heat flow, electrical, and electromagnetic (EM) data, and of hydrological systems and thermally induced convection. This modeling should include multiple data set forward and inverse approaches.

2.2.5.2 Constraints

By use of existing computer programs and those developed in 1) above, establish the basic constraints required for reservoir modeling and identify which of the physical and chemical observables from surface and borehole studies are the most important. To this end it is most important to fund studies which will improve our ability to predict (listed in order of decreasing importance):

a) porosity and permeability

b) fluid properties, and

c) pressure.

It is the belief of the consortium that funding of technology development for improvement of electrical geophysical surveys (MT, EM, IP, resistivity) show the greatest promise in this regard.

2.2.5.3 Data Collection

Once the basic constraints are established,

specify data collection regarding type and accuracy needed to define geothermal systems. This will have obvious near-term payout to exploration, confirmation and assessment, and to reservoir engineering.

2.2.5.4 Conceptual Models

Concurrently with 1), 2), and 3) form simplified conceptual models of geothermal systems in a number of geological environments which take account of existing data on subsurface conditions in known reservoirs.

2.2.5.5 Compare

Using existing numerical techniques and those developed in 1), perform forward modeling of the conceptual geothermal models from 4), and compare predicted physical and chemical parameters with observed data. Adjust the conceptual models, and reiterate the process until all data sets are adequately modeled.

2.2.5.6 Inverse

Establish the inverse computer programs needed to go directly from a set of surface and borehole observations to a geothermal reservoir model.

Progress in reservoir modeling techniques could have immediate payout in areas such as Roosevelt Hot Springs and the Valles Caldera, where industry must site and drill a large number of holes in order to get power on line. It is established that roughly 20 more holes must be drilled at Roosevelt Hot Springs alone in order to reach the 110 MWe currently planned. These

holes can be expected to average $750,000 each. A better understanding of the reservoir and of the geological, geophysical and geochemical data collected over this reservoir would facilitate hole placement, with savings of both money and time.

2.2.6 (N,M) Rock Properties

The justification for measurements of rock properties is contained under 2.1.6 above. Not included there because they fall into the exploration technology category are the following:

2.2.6.1 High Temperature Handling Techniques

Develop techniques for measuring rock properties and handling brines at temperatures in excess of 250°C.

2.2.6.2 Modeling Resources

Develop techniques for modeling reservoirs based on rock and fluid properties.

These activities are supportive of the resource evaluation and reservoir confirmation activities of 2.1.6 and should involve the same rock properties as listed there.

2.2.7 (M,F) Igneous Processes

Development of exploration technology in the mid- and far-term utilizing igneous processes is a responsibility of the U.S. Geological Survey and hence no recommendations concerning it are included here.

2.2.8 (N,M,F) Exploration Strategy

Exploration strategy is directed toward maximizing the information return while (ideally) minimizing costs of a modular exploration sequence. Development of geothermal exploration strategies is still in its infancy and requires considerable federal effort a) in the near-term for detecting and delineating geothermal resources for which surface manifestations exist, b) in the mid-term for detecting and delineating totally hidden resources, and c) in the far-term for detection and delineating regions where high temperatures are at shallowest depth.

The cost-effectiveness of the individual modules of and of the complete exploration strategy is best accomplished with the aid of case histories where subsurface information is available. Accordingly, it is recommended that the following be federally funded:

2.2.8.1 Exploration Strategies

Develop cost-effective exploration strategies referenced to case studies for which subsurface information is available via both productive and non-productive wells. The preferred exploration strategy is to be compared with real or hypothetical alternate strategies.

2.2.8.2 Pattern Recognition

Apply survey design methods such as pattern recognition, which might be used to optimize exploration investments, referenced to real field data.

3.0 Budgetary Estimates

These estimates are the author's but are based largely on the program review process with allowance for growth, project terminations, and cost escalation. If the total amounts recommended are beyond the scope of the DOE/DGE program in any given year, they can be used as indicators of relative levels of recommended spending within the various categories. All figures are in millions of dollars.

3.1 Resource Evaluation and Reservoir Assessment

3.1.1 Thermal Methods

3.1.1.1 Regional Thermal Measurements, Free Holes

FY79	FY80	FY81	FY82	FY83	FY84
1.0	1.1	1.2	1.3	1.4	1.5

3.1.1.2 Regional Shallow Drilling

FY79	FY80	FY81	FY82	FY83	FY84
1.0	1.1	1.2	1.3	1.4	1.5

3.1.1.3 Drill and/or Preserve Deep Holes

FY79	FY80	FY81	FY82	FY83	FY84
1.0	1.2	1.4	1.6	1.8	2.0

3.1.1.4 Collate Data

	FY79	FY80	FY81	FY82	FY83	FY84
	0.5	0.6	0.7	0.8	0.9	1.0
Totals	3.5	4.0	4.9	5.0	5.5	6.0

3.1.2 Water/Rock Interaction

	FY79	FY80	FY81	FY82	FY83	FY84
Reservoir Confirmation						
Western non-electric	.125	.205	.275	.350	.425	.500
Eastern non-electric	.125	.150	.175	.200	.225	.250
Pre-commercial	.200	.225	.250	.275	.300	.325
Industry-coupled	.200	.400	.800	1.00	1.200	1.400
Totals	.650	.975	1.500	1.825	2.150	2.475

3.1.3 Electrical Methods

3.1.3.1 Case Histories

FY79	FY80	FY81	FY82	FY83	FY84
.30	.60	1.20	1.50	1.50	1.50

3.1.3.1 Comparative Studies

FY79	FY80	FY81	FY82	FY83	FY84
0.10	0.15	0.20	0.10	-	-

3.1.3.3 Regional Electrical Data Base

	FY79	FY80	FY81	FY82	FY83	FY84
Planning	.15	.15	.15	.15	.15	.15
Surveys	-	-	.80	1.20	1.60	2.00
TOTALS	FY79	FY80	FY81	FY82	FY83	FY84
	0.55	0.90	2.35	2.95	3.25	3.65

3.1.4 Seismic Methods

	FY79	FY80	FY81	FY82	FY83	FY84
3.1.4.1 Data acquisition & interpretation, areas previously drilled.	1.5	2.0	2.5	3.0	3.5	4.0
3.1.4.2 Environmental Monitoring (120K installation & (80K operating costs)	2.00	2.0	4.0	6.0	8.0	10.0
Totals	2.5	4.0	6.5	9.0	11.5	14.0
Sites	5	10	20	40	80	100

3.1.5 Reservoir Modeling

	FY79	FY80	FY81	FY82	FY83	FY84
3.1.5.1 World Wide Inventory	.100	.150	.200	.300	.300	.300
3.1.5.2 Site Specific Application of Exploration Technology	.200	.400	.600	.800	1.00	1.200
Totals	.300	.550	.800	1.100	1.300	1.500

3.1.6 Rock Properties

3.1.6.1 Measurements	FY79	FY80	FY81	FY82	FY83	FY84
Develop Laboratory Capabilities	0.50	0.50	0.50	-	-	-
Rock Property Measurements (Case Histories)	2.00	2.00	2.00	2.00	2.00	2.00
Rock Property Measurements (Ongoing)	0.50	1.00	2.00	2.50	3.50	4.50
Data Dissemination & Utilization	0.70	0.80	0.70	0.70	0.70	0.70
3.1.6.2 Coring						
Funds for Coring	1.00	1.00	1.50	-	-	-
Totals	4.70	5.30	6.20	5.20	6.20	7.20

3.1.7 Igneous Processes

	FY79	FY80	FY81	FY82	FY83	FY84
Site Specific Studies	.60	.80	.90	1.00	1.10	1.20
Data utilization and assimilation	.05	.10	.15	.20	.25	.30
Totals	.65	.90	1.05	1.20	1.35	1.50

3.1.8 Total Budgetary Estimate

	FY79	FY80	FY81	FY82	FY83	FY84
Thermal Methods	3.5	4.0	4.5	5.0	5.5	6.0
Water/Rock Interaction	.65	.875	1.5	1.83	2.15	2.48
Electrical Methods	.55	.90	2.35	2.95	3.25	3.65
Seismic Methods	2.5	4.0	6.5	9.0	11.5	14.0
Reservoir Modeling	.30	.55	.80	1.10	1.30	1.50
Rock Properties	4.70	5.30	6.20	5.20	6.20	7.20
Igneous Processes	.65	.90	1.05	1.20	1.35	1.50
TOTALS	12.85	16.53	22.90	26.28	31.25	36.33

The above budgetary forecasts do not include the costs of a) operating the state-coupled program, b) operating the industry-coupled program, c) headquarters, national laboratories, and contractors concerned with program planning and management, d) the outreach program, e) exploration technology development, nor f) operating the Raft River Facility.

3.2 Exploration Technology

3.2.1 Thermal Methods

	FY79	FY80	FY81	FY82	FY83	FY84
3.2.1.1 Portable Temp. Logging Gear	0.20	-	-	-	-	-
3.2.1.2 In Situ	.20	.40	.50	.25	-	-

Thermal Conductivity Gear						
3.2.1.3 Laboratory Thermal Conductivity Gear	.20	.25	.25	.10	-	-
3.2.1.4 High Temp. Logging Gear	.20	.20	.10	.10	-	-
3.2.1.5 Thermal/ Hydrologic Case Histories	.30	.45	.50	.65	.80	.90
3.2.1.6 Theoretical Thermal/Hydrologic Studies	.30	.45	.50	.45	.45	.45
Totals	1.40	1.75	1.85	1.55	1.25	1.35

3.2.2 Water/Rock Interaction

3.2.2.1 Sample Analysis	0.15	0.20	0.20	0.20	0.10	0.05
3.2.2.2 Synthesis of Studies	1.00	1.10	1.20	1.30	1.40	1.50
Totals	1.15	1.30	1.40	1.50	1.50	1.55

3.2.3 Electrical Methods

	FY79	FY80	FY81	FY82	FY83	FY84
3.2.3.1 State-of-	.20	.10	.10	.10	.10	.10

the-art capabilities						
3.2.3.2 Methods used in consort	.20	.20	.20	.20	.10	.10
3.2.3.3 2-D, 3-D Interpretation	.30	.40	.60	.60	.30	.30
3.2.3.4 AMT/MT Problems	.20	.20	.20	.15	.05	-
3.2.3.5 SP Method	.05	.10	.10	.10	.05	-
3.2.3.6 Time and frequency domain	.05	.10	.10	-	-	-
Totals	1.00	1.10	1.30	1.15	.60	.50

3.2.4 Seismic Methods

3.2.4.1 Passive	1.00	0.50	0.50	-	-	-
3.2.4.2 Seismic Network Interpretation	0.50	0.50	0.25	-	-	-
Totals	1.50	1.00	0.75	-	-	-

3.2.5 Reservoir Modeling

	FY79	FY80	FY81	FY82	FY83	FY84
3.2.5.1 Multiple Data Set Modeling	.40	.50	.60	.60	.60	.50
3.2.5.2 Constraints	.20	.25	.30	.40	.40	.40
3.2.5.3 Data	.05	.10	.15	.15	.15	.15

Collection						
3.2.5.4 Conceptual Models	.15	.25	.30	.35	.40	.40
3.2.5.5 Compare	.15	.20	.30	.35	.40	.40
3.2.5.6 Inverse	.05	.10	.25	.40	.45	.50
	1.00	1.40	1.90	2.25	2.40	2.35

3.2.6 Rock Properties

	FY79	FY80	FY81	FY82	FY83	FY84
3.2.6.1 High temp. handling techniques	1.00	1.50	1.50	1.00	0.50	0.50
3.2.6.2 Modeling resources	0.25	0.50	0.50	0.50	0.50	0.50
	1.25	2.00	2.00	1.50	1.00	1.00

3.2.7 Igneous Processes - no funding recommended

3.2.8 Exploration Strategy

3.2.8.1 Exploration Strategies	.5	1.0	1.5	1.5	0.5	-
3.2.8.2 Pattern Recognition	.25	.50	.50	.50	.25	.25
	.25	1.50	2.00	2.00	.75	.25

3.2.9 Total Budgetary Estimate

	FY79	FY80	FY81	FY82	FY83	FY84
3.2.9.1 Thermal	1.40	1.75	1.85	1.55	1.25	1.25

Methods							
3.2.9.2	Water/Rock Interaction	1.15	1.30	1.40	1.50	1.50	1.55
3.2.9.3	Electrical Methods	1.00	1.10	1.30	1.15	.60	.50
3.2.9.4	Seismic Methods	1.50	1.00	0.75	-	-	-
3.2.9.5	Reservoir Modeling	1.00	1.40	1.90	2.25	2.40	2.35
3.2.9.6	Rock Properties	1.25	2.00	2.00	1.50	1.00	1.00
3.2.9.7	Igneous Processes	-	-	-	-	-	-
3.2.9.8	Exploration Strategy	0.75	1.50	2.00	2.00	0.75	0.25
		8.05	10.05	11.20	9.95	7.50	6.90

REPORTS OF CONSORTIA

4.1 Thermal Methods

RECOMMENDATIONS OF THERMAL METHODS PANEL

INTRODUCTION

This report represents recommendations developed at the first meeting of the Thermal Methods Advisory Panel of DOE/DGE. The panel met on November 29, 1977, at the AMAX Exploration office in Denver, Colorado. Those present at the meeting included David D. Blackwell, Southern Methodist University (chairman); David Chapman, University of Utah; Richard Dondanville, Union Oil Company; Arthur Lachenbruch, U.S. Geological Survey; Arthur Lange, AMAX Exploration Inc.; and Chandler Swanberg, New Mexico State University. This set of recommendations represents the consensus reached by this group during the meeting and in subsequent correspondence, and we submit this report for consideration to the DOE/DGE.

SUMMARY

The scope of thermal methods in geothermal studies is defined, and it is pointed out that these methods are unique in geothermal exploration in that they, in some sense, measure directly the major quantity of interest in geothermal exploration, i.e. heat. Results of an industry survey show that typically 50% of the geophysical exploration budget is expended for these types of exploration, and that these techniques are considered very important or the most important geophysical techniques used in geothermal exploration. The position of thermal methods in the government geothermal development program is also discussed. A proposed program of thermal measurements is discussed, including a crash program of regional studies in order to prepare a detailed thermal map of the United States. This regional studies program would probably have the most significant impact on the proposed DOE/DGE target figure of 20,000 MWe installed capacity of any program proposed or in progress in the resource evaluation and reservoir confirmation part of the geothermal program.

DEFINITION

After some discussion, we decided to call ourselves the Thermal Methods Panel. The scope of this panel is defined to include all techniques that involve the direct measurement of earth heat and its use in exploration, assessment and evaluation of geothermal systems. Included in these measurements of earth heat may be components from a number of different heat transfer sources, including specifically convective heat transfer and conductive heat transfer. Techniques

which come directly under the overview of this panel include those relating in one way or another to direct measurements of temperature. These techniques can be divided into approximately four subcategories as follows:

1) the measurement of temperature alone, which may be used for interpretation without any attendant measurement of other geophysical or geological parameters.
2) measurement of geothermal gradient, calculated as the vertical variation of temperature (usually, but not always, from measurements made in a borehole).
3) measurement of heat flow, which involves measurement of thermal conductivity and calculation of heat flow from the product of geothermal gradient times thermal conductivity.
4) the measurement of heat budgets, either by surface measurements of spring flow rate and temperature, or by integration of areal heat flow data.

Associated with these techniques may be attendant measurements of such quantities as thermal conductivity, fluid flow velocity, porosity and permeability. Knowledge of these quantities may be necessary in order to interpret the nature of the heat transfer in the system.

Thermal techniques are unique in geothermal exploration in that they directly detect the necessary component of the geothermal system, i.e. heat. Ideally the data can yield quantitative estimates of the heat present. No other geothermal exploration technique has this direct correspondence with the quantity desired. There is no analogous technique of exploration in the petroleum industry, where all exploration techniques involve indirect measurement of quantities which may or may not be related to the presence of hydrocarbons.

CHARACTERISTICS OF THERMAL MEASUREMENTS

As defined, thermal methods include the direct measurement of some or all of such quantities as temperature, geothermal gradient, heat flow, heat budget, thermal conductivity, fluid flow velocity, porosity and permeability. In general, although not always, these measurements will be made in drill holes. The purpose of these studies is to obtain data for correlation and comparison with other exploration results in order to identify the location, quality (temperature) and size of geothermal resources.

The scale of these measurements is highly variable both in a lateral and vertical sense, and in general, the spacing depends on the objectives of the program and the cost-effectiveness of various scales of measurement.

This panel recognizes five depth scales for thermal measurements:

a) Measurements made in the holes that are less than three meters deep fall into the first category. In these cases, holes may be drilled with hand or power operated augers (in soft rocks, at least). Temperatures are measured and a correlation of temperature is directly made with heat.

b) The second category involves holes which are on the order of 30 m deep. In these cases, temperature gradient or heat flow measurements may be made. In general, microclimatic effects, seasonal variations, and shallow groundwater flow will be major noise sources for these types of measurements.

c) The third scale of measurement involves holes from 30-150 m deep. In general, these techniques involve gradient or heat flow studies. Surface noise from microclimatic effects, shallow groundwater aquifers, and seasonal variations is minimal, although larger scale effects of many kinds may be present. The 150 m depth is arbitrary and is at the present time defined by the regulatory system.

d) Measurements made in holes deeper than 150 m may be classed in a fourth category, and in these cases, measurements of the appropriate quantities may be the most complete.

e) A fifth classification involves measurements of thermal properties in deep (usually greater than 1 km) exploration and production drill holes. Dynamic variations of temperature and other thermal properties associated with drilling, intra-borehole flow, and production are measured and interpreted.

Knowledge of the thermal regime in geothermal systems observed at any depth of study must ultimately be tested against the ability to give information on the size, shape, temperature, flow conditions, etc., of the geothermal reservoir as determined by production and exploration tests.

A class of exploration not included above might include such techniques as SP measurements, if SP as measured in geothermal systems is directly related to temperature.

Heat budget measurements may involve temperature and flow rate from a spring, or may involve more complicated studies, including areal averaging of temperature gradient or heat flow measurements.

The spacing of holes will also vary greatly in a lateral sense. In areas where the various factors affecting the heat flow vary over a relatively long distance, perhaps on the order of a crustal thickness or so, regional heat flow measurements with a spacing of 50-100 km are satisfactory for obtaining a regional background heat flow distribution. In more complicated areas, where variations occur more rapidly, a much closer spacing of data is necessary in order to properly evaluate regional variations. In such areas, heat flow or thermal measurements on a scale of 5-20 km are necessary for complete regional coverage. For example, typical geothermal systems may have geophysical expressions that range from a few hundred square kilometers down to a few tens of square kilometers. For complete prospect identification in the western United States, it is estimated that ultimately thermal measurements at a spacing of five kilometers will be necessary. In order to actually delineate a geothermal anomaly defined by regional studies or by some other technique, much more detailed measurements are necessary. In general, the spacing of the measurements must be close enough so that inflection points between high and low values can be located. This spacing may vary from a hundred meters to several kilometers, although in general, the spacing will be less than one kilometer.

SIGNIFICANCE OF THERMAL MEASUREMENTS

It might appear that the significance of thermal measurements to geothermal energy is obvious; however, it appears to this panel from past experience that the relationship has not been generally appreciated. The situation is changing somewhat at the present time, but it is still not clear to the panel that thermal measurements occupy a role in the federal program in proportion to their significance. Thermal measurements directly identify and ideally, uniquely measure the quantity desired (heat); therefore, in exploration, confirmation, development and evaluation programs, no matter what the order of application of various geological and geophysical techniques, ultimately thermal measurements will be made. Very often these measurements will span the whole life cycle of a prospect. The object of the first meeting of this panel was to identify the position in the spectrum of government programs which should be occupied by the thermal measurements, and to recommend the types of studies to be part of the program, so that industry can reach the goals set out for geothermal industry in the future, i.e. an ultimate production figure of at least 20,000 MWe.

Since thermal measurements must be made at some point during the cycle in any event, this panel believes that much time is already lost in obtaining the necessary data. A program to fill this gap is discussed in a following section.

INDUSTRY SURVEY

In designing any government program, a number of different users need to be kept in mind. One of the main users of the results of the geothermal program will be the geothermal industry itself. The panel felt it was important, therefore, at the beginning of these deliberations, to consider the directions of interest to industry. During the month of December, twelve major companies involved in geothermal exploration were contacted and asked several questions relevant to thermal methods exploration. The following questions were asked of Aminoil, AMAX, Chevron, Union, Getty, Sundeco, Thermal, Occidental, Republic, Phillips, Earth Power and Hunt:

1) On a quantitative basis, what is the importance of gradient/heat flow holes in a geothermal exploration program?

2) What portion of your geophysical budget is devoted to gradient holes?

3) Approximately how many gradient holes do you drill per year?

4) What is the approximate cost of a hole 100-150 m deep?

The data are tabulated in Table 1. Individual companies are not identified in Table 1, because several exploration managers requested anonymity. The most common response was that gradient/heat flow techniques were a very important part of the geothermal exploration program. An estimate of about 50% of the geophysical exploration budget is spent on these sorts of measurements, although the percentage actually varies from a mere 5% in one case to over 75% at the other extreme. It appears that a very large number of holes (1000+) are being drilled each year by industry. This activity contrasts with the total number of published heat flow values up to the present time, which are listed as 625 by Lachenbruch and Sass[1]. The average cost figure for different holes is obviously very rough, and different companies drill different depth holes, make thermal measurements in different ways, and for Table 1 some companies estimated drilling cost alone, while others included staff overhead, etc.

These results form a basis, if the intrinsic usefulness of thermal measurements does not, for justifying a large federal program in thermal measurements applied to geothermal studies. In addition, the exploration managers were asked to suggest government-funded projects which might be most beneficial to their activities. The consensus of opinion includes:

1) Regionally-spaced shallow gradient holes, with a few deep holes for calibration. DOE should avoid prospect delineation.

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1. Lachenbruch, A.H., and J.H. Sass, Heat flow in the United States and the thermal regime of the crust, American Geophysical Union Geophysical Monograph, in press, 1978.

TABLE I

GRADIENT HOLE ACTIVITY OF GEOTHERMAL EXPLORATION COMPANIES

COMPANY	QUALITATIVE IMPORTANCE OF GRADIENT/HEAT FLOW HOLES IN EXPLORATION PROGRAM	PORTION OF GEOPHYSICAL BUDGET TO GRADIENT HOLES	NUMBER OF HOLES PER YEAR	AVERAGE HOLE COST * (100-150 METERS DEPTH)
A	Very important, but complicated by hydrology	5%	10	$6,000-8,000
B	Most important	30-35%	175	$2,000-2,200
C	Most important, direct sensor of resource	75%	100+	$2,400
D	Very important, after regional analysis	50%	100+	$3,000
E	First method used in most areas	35-50%	20-60	Variable $4-15/foot
F	Most important, first method used	75-100%	125+	$5,000, including thermal conductivity
G	Very important	60%	70	$6,000-8,000
H	Very important, after resistivity	20%	7-10	Variable, area dependent
I	Very important	50%	125	$1,000-2,000
J	First method used after regional analysis	15%	50	$3,000-5,000
K	Most important after regional analysis	35-45%	50-75	$2,500-3,500
L	Fundamental parameter. Very important	50-55%	100+	$2,500-3,000

* In some cases only drilling costs are included, in others data reduction, staff overhead, etc. are included.

2) Completion of a heat flow map of North America including holes in the mid-continent and on a geologic province basis in the western part of the continent.

3) Acquisition of petroleum dry holes for long-term deep heat flow measurements. There are several areas where geothermal prospects are relatively close to petroleum prospects: western Sacramento Valley, California, Snake River Plain, Rio Grande Rift, Oregon, Washington, Nevada and Utah.

4) Research on the effect of hydrology and terrain upon shallow measurements.

Industry is particularly interested in the effect of ground water flow on heat flow measurements made in relatively shallow holes.

PROPOSED PROGRAM

On the basis of this initial meeting and the industry survey discussed above, a number of obvious important aspects that all committee members believe should be included in the national program for geothermal development have emerged. There is a high degree of correlation between the program needs of industry and government, in particular the need to evaluate the resource (find anomalies) in order to move toward the optimistic goals set for geothermal development. In particular, we believe that:

1) A systematic and extensive program of making measurements in available drill holes should be implemented as soon as possible and at a relatively high level of funding.

2) A systematic drilling program should also be implemented as soon as possible. This drilling should include one hundred to five hundred holes per year, to depths of 100 to 150 m, spaced in such a way to fill in the gaps in the free hole data and to investigate specific provinces and problems. These holes should not be drilled in order to delineate specific geothermal reservoirs, however.

3) A major program should be undertaken to utilize deep holes drilled for other purposes.

4) Development of new and improved techniques of thermal measurements and their interpretation should be pursued.

5) Detailed studies of the effects of fluid flow on thermal measurements should be carried out.

The most cost-effective way to geophysically explore for geothermal resources is to make thermal measurements in holes drilled for other purposes. At the present time, tens of thousands of holes are drilled in the United States every year, and many of these holes could be used for thermal measurements as well. Measurements in these holes typically average $100 to $500 apiece, a factor of more than 10 less than measurements in specially drilled holes. Such techniques may be the only effective geophysical way to explore for low-temperature resources where expenses of exploration are critical. It is particularly convenient that much of the current drilling involves water wells drilled within 50 km of major cities. This type of activity gives information on medium-temperature resources that would be financially unfeasible to obtain otherwise. These types of measurements also give data in areas of possible high temperature electrical resources.

The "free" hole types of studies are not complete alone, however. Such studies must be combined with targeted drilling programs in order to complete geographical coverage, to investigate particular problems, and to delineate particularly attractive regional geothermal targets. These two sorts of programs should be carried out all over the United States with a higher density in the western United States than the eastern United States, because of the more rapid variation in heat flow associated with the complex structure and geology of the western United States and the greater ultimate electrical energy potential. Numerous holes of all depths are drilled by government agencies; in particular, deep wells are often drilled by the U.S.G.S. Water Resources Division and by DOE for such activities as uranium exploration. It ought to be possible to require government agencies planning deep drilling to specify how they intend to obtain thermal measurements from all wells they drill, for input into the geothermal resource analysis program.

Of particular interest are holes that are drilled in the 600-1000 m range, considerably deeper than those available for large-scale regional measurements of the type discussed above. Such holes are drilled for mineral exploration, especially base metals and uranium, for water, and for petroleum exploration. Petroleum exploration holes are not very useful for geothermal studies becuase they are almost invariably cemented shut before useful thermal measurements can be obtained. However, in most cases, intermediate casing strings are set to 600 to 1000 m. Typically, upon abandonment, a cement plug is put at the bottom of this casing string, and a second cement plug at the top of the casing string. This is the typical abandonment procedure required by most states in order for performance bonds to be released. We believe a systematic program sponsored by DOE to temporarily take responsibility for final abandonment of these holes according to state regulations would be extremely valuable. These holes could then be allowed to sit and reach thermal equilibrium before final abandonment. Final abandonment porcedures would cost far less than the drilling of equivalent depth holes specifically for geothermal studies. In addition,

deeper temperature data may be available from the bottom hole temperature measurements during the logging of the well before abandonment. In addition, a few holes to depths not greater than 1 km should be drilled in various provinces to test out the areas where shallow results have problems or are suspect. A prime example of this would be the Snake River Plain in Idaho. Perhaps ten holes might make a program of this sort (annually).

We believe that these first three programs ought to be undertaken on a crash program basis by DOE. Far too much time has already been lost when a more complete reservoir confirmation process could have been in progress for the United States. We believe that with this sort of program, complete thermal measurement coverage for the United States (at the scale of approximately one measurement per 100 km^2 in the western United States, and one per 1000-2000 km^2 in the central and eastern United States) can be completed in approximately five years. *This program would probably have the biggest impact on the proposed DOE/DGE target figures of 20,000 megawatts installed cepacity of any program proposed or in progress.*

In addition, we believe extensive programs should be funded by DOE/DGE for development of interpretation techniques. These sorts of studies ought to be funded to the level of at least several hundred thousand dollars per year. Proposed improvements in techniques should be supported at a relatively high level; for example, shallow hole techniques and in situ measurements might be the subject of systematic technique improvement studies supported by DOE/DGE. Interpretation techniques including modeling, continuation and effects of thermal conductivity contrasts should be supported.

There should be a central clearinghouse available for thermal data, and some entity in charge of preparing heat flow maps of the United States. Also, available thermal property information collected by university and government investigators should be summarized for use in the industry and by the research and development community. For example, many thousands of thermal conductivity measurements have already been made, and this data should be available in summary form for use.

Studies of the effect of ground water flow for shallow heat flow measurements ought to be funded at a relatively high level. Several test areas ought to be selected where simultaneous hydrologic and thermal measurements could be made in a very detailed way, both on a long-term basis and on a basis of correlation with hydrologic parameters so that the actual effect of ground water flow can be clearly and completely understood. Finally, combined technique studies in areas for which large amounts of exploration data are already available should be continued and brought to completion as case study situations. Empahsis ought to be on the areas which have already been studied, rather than outlining and exploring new areas.

A proposed budget for thermal methods in the DOE/DGE geothermal program is shown in Table 2. This budget is based on a slightly higher level of geothermal funding than is available for the current fiscal year, although current figures for this fiscal year ought to be 60% or more of those shown in Table 2. We believe funding of this program ought to be undertaken on a crash basis. This sort of program should have been initiated much earlier in the geothermal program, and much lost time must be made up if we are to properly evaluate the geothermal resources and confirm the existence of geothermal reservoirs of the quantity and quality necessary to make geothermal a viable energy source. No one particular budget item is considered inflexible; rather, this budget attempts to give a rough idea of our level of assessment of the importance of the various techniques. To some extent, there is also interaction between the outlined budget items in that many of the regional measurements will supply field data for study of the effects of hydrology on heat flow. Therefore this part of the program as budgeted can deal specifically with theoretical studies of the field measurements rather than with the field measurements themselves.

TABLE 2. Proposed Thermal Measurements Budget
(Annual for 5 years)

	Budget
Regional Thermal Measurements, free holes (2000/year)	$1,000,000
Regional Shallow Drilling (≤ 150 m -- 100-500 holes/year)	1,000,000
Deep Thermal Measurements (10 holes, plus preservation program)	1,000,000
Collection of new and existing data	500,000
Developmental Techniques	600,000
Interpretation and Modeling	300,000
Effects of Hydrology on Heat Flow	500,000
	$4,900,000

4.2 Water/Rock Interaction

FIRST REPORT OF THE CONSORTIUM ON WATER/ROCK INTERACTION IN RELATION TO EXPLORATION TECHNOLOGY AND RESERVOIR EVALUATION

December 9, 1977

I. BENEFITS FROM STUDIES OF WELL AND SURFACE SAMPLES

Studies of fluid samples (liquid and gas) and solid samples (cores and cuttings) collected from geothermal wells and from the earth's surface have important bearing on many facets of geothermal development. These facets can be grouped into two broad categories: (1) exploration technology, and (2) reservoir evaluation.

EXPLORATION TECHNOLOGY

Geothermal exploration consists of measuring various geophysical, geochemical, and geological parameters at the earth's surface and interpreting these parameters in terms of a working model of subsurface conditions. This model has three sets of constraints: (1) the physical constraints imposed by the measured data themselves, (2) the degree to which the model reflects reality, and (3) the nature of the target and its associated physical and chemical features.

Exploration does not necessarily involve sets 2 and 3, for it is perfectly possible to drill on any uninterpreted anomaly. The drillholes may indeed by a success, but will give little information on which to base other exploration ventures and will not enhance the development of realistic models. Intelligent geothermal exploration, however, involves careful determination of the surface and subsurface parameters in order to learn what is causing the geophysical, geochemical, and geological signatures observed at the earth's surface and to develop realistic models of geothermal 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 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.

Geophysical Methods

Geophysical methods are used primarily to delimit the location and likely geometry of a geothermal system, both by determining zones of anomalous heat flux, electrical conductivity, or microearthquakes, and by defining subsurface geologic structure (eg. with active seismic surveys). Refinement of geophysical methods requires study of cuttings and core to determine physical properties, mineralogy, rock type, and stratigraphy, as well as analysis of fluid samples to determine electrical conductivity and the relation of surface electrical signals to underground parameters. Careful correlation of surface geophysical signals with surface and subsurface samples may enable us to develop ways of predicting subsurface temperature, porosity, permeability, and type of reservoir fluid.

Geochemical Methods

Presently used geochemical surveys are of two types: (1) chemistry of springs, fumaroles, or shallow drillholes 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 soils 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.

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.

Geological Methods

Geological methods are presently used in reconnaissance to locate surface indications of geothermal systems, and in detailed studies to locate and characterize rock type and distribution, mineralogy, structure, fracturing, hydrothermal alteration and other parameters. Better understanding of the interactions between fluid and rock will markedly enhance the ability of the geologist to interpret his observations and to extrapolate into unsampled volumes of rock in three dimensions. Ultimately it may be possible accurately to evaluate raw prospects, to predict the location of reservoir rocks and cap rocks, and to provide real-time drilling guidance.

RESERVOIR EVALUATION

Once a geothermal reservoir is discovered, the next step is to determine its nature and potential. Short- and long- term production tests clearly are a first priority, but are not sufficient to characterize the reservoir and allow intelligent development decisions. In addition, careful study of subsurface rocks and fluids is necessary. The economics of any geothermal development are critically dependent on the definition of potential scaling or corrosion problems, the prediction of continued aquifer productivity, and the assurance that injection wells will continue to accept effluent. These three aspects are controlled by rock-water interaction, and their evaluation thus requires careful determination of the solid and fluid phases in and around the reservoir.

Drilling and completion

Development drilling is guided by the geologic structure and hydrologic conditions of the reservoir, both with respect to well location and drilling procedure (eg. nature and composition of drill fluid, casing

program, completion procedures, etc.). The geologic structure can be determined only by careful study of cuttings and core and the correlation of these studies with geophysical surveys and borehole log interpretation. Borehole logs alone are not sufficient, for log responses in high-temperature environments are poorly understood and interpretation has not been calibrated for the rock types and temperatures found in geothermal systems. Furthermore, studies of alteration mineralogy and fluid samples from specific horizons can supply information critical to completing the well at the optimum, hot zone.

Reservoir assessment

Assessment of geothermal reserves and resources of a given area is not merely the determination of productivity, temperature and reservoir size. It also involves evaluation of the characteristics of the fluid and their probable variation with time. Not only is the available work from a reservoir fluid dependent on salinity, but certain fluid compositions may require expensive surface treatment, with consequent adverse effects on economics.

Field management and reservoir utilization

Studies of fluids and gases produced from geothermal wells are absolutely essential to effective field management and reservoir utilization. The nature of the fluid dictates the materials chosen for piping, hardware, turbines, heat pumps etc. Furthermore, the thermodynamic properties of the fluid and the nature and concentration of gases are essential information for the optimum design of generating equipment. Finally, knowledge of fluid compositions and their likely change with time is required for the identification of potential scaling problems and the identification of realistic scale prevention methods.

Fluid-rock interactions, subsurface boiling, and dilution by non-geothermal waters strongly impact the evolution with time of fluid compositions and flow rates. Studies of the mineralogical, isotopic, and trace element relationships in reservoir rocks and the chemistry and isotopes of associated fluids allow prediction of possible changes in reservoir character and fluid composition and quality with exploitation, and can identify potential precipitation and alteration reactions that could reduce permeability with time. In particular, studies of mineralogy, physical properties, and fluid chemistry in potential injection zones are of critical importance in order to predict in advance any possible chemical reactions and resultant decrease of permeability during reinjection.

II. FY-78 IMPLEMENTATION

NATIONAL SUPPORT

DOE-funded geothermal wells are being drilled or are planned at a number of locations under several different programs of the Division of Geothermal Energy. It is important that a systematic program of sample acquisition, storage, distribution and study be set up immediately so that maximum benefit can be realized from the unusual opportunities presented by these expensive wells. DOE support and funding should be provided in the following areas: (1) sample acquisition, (2) sample curation, preparation and distribution to researchers, (3) generation of basic background data, and (4) detailed characterization and study of samples.

Sample acquisition

Samples should be collected carefully and completely from each DOE-funded geothermal hole, ideally under the direction of an experienced earth scientist using established procedures. To this end, a manual for collecting, labeling and packaging solid and fluid samples should be completed.

DOE contracts under the Industry-Coupled Program and other programs should call for a complete suits of appropriate samples from each hole.

Sample curation, preparation and distribution

Present plans are to store rock samples from some DOE-funded geothermal holes at the University of Utah Research Institute. The primary objectives of the to-be-created Geothermal Sample Library are (1) to supply geoscientists from government, academia, and private industry with samples appropriate to their research needs, and (2) to collect under one roof rock samples and/or sample abstracts from many geothermal wells for examination and comparison. Curation and distribution methods are being worked out at present, and consideration is being given to the storage of fluid samples as well as rock samples.

Funding should be provided by DOE to support this facility. In addition, funding should also be provided to curate, prepare and distribute samples from collections stored elsewhere. Curation and preparation procedures at all libraries should be standardized.

Generation of basic background data

In order to facilitate determination of the scope and priority of research work to be performed on geothermal rock samples, certain basic data should be generated on samples from each geothermal well. These basic data would include (1) lithologic description, (2) mineralogy, (3) analyses of selected major, minor and trace elements, and (4) selected physical properties such as density and magnetic susceptibility. These data should be collected systematically on composites of cuttings and on selected core. It is anticipated that this work is best done at UURI in conjunction with activities of the Geothermal Sample Library.

Detailed characterization and study of samples

Samples from DOE-funded geothermal wells should be made available for detailed studies as appropriate, and provision should be made by DOE/DGE to fund such studies. It is anticipated that coordination of different studies of the same sample suite in the Geothermal Sample Library would be coordinated by UURI, with the aid of an independent advisory board if required. Research proposals would be directed to DOE/DGE or its designate, with the Geothermal Sample Library of course being open to all qualified investigators regardless of fund source.

REGIONAL AND RESERVOIR INVESTIGATIONS

All regional and reservoir investigations supported by DOE/DGE should have appropriate components dealing with sampling and study of rocks and fluids from geothermal wells and from the earth's surface. Rocks and fluids are normally sampled and analyzed separately, but interpretation of results requires integration of both data sets, along with supplementary borehole logs and geological information.

Fluid and rock samples present different kinds of problems and opportunities, which require separate consideration. A fluid sample at the well-head is a mixture derived from the whole production interval, which has been fractioned into noncondensible gas, steam and water phases in transit up the borehole to the sample bottle. Rock samples are much more heterogeneous and so require more detailed studies. Both types of sample are subject to contamination by drilling muds and fluids. Whereas rock samples can normally only be acquired during the initial drilling, fluid samples should be acquired during the whole lifetime of a producing geothermal well. The level of technical effort required for the collection of fluid and rock samples also differs. It is technically difficult to collect a representative fluid sample. Precise control of the flow rate, well-head pressure

and knowledge of the enthalpy and mass ratio of the steam-water mixture is necessary. Analysis must begin at the well-head and pH meters, conductivity bridges, reagents and stabilizing solutions, etc., employed. Thus collection should be performed by technical personnel who have been carefully trained by geochemists experienced in geothermal problems. In contrast, well-site rock sampling requires less technically difficult skills and only the general supervision of a geologist to advise on the sampling program and procedures.

The investigations of fluid and rock samples recovered from a specific geothermal well will depend heavily on the local circumstances of the drilling program and the geological environment of the site. The studies to be performed depend upon the stage reached in a drilling program. The intensity of work done on sample from wildcat wells in-filling and step-out exploration wells, production wells, and reinjection wells is likely to be different. Accordingly, it is impossible to specify a priori exactly what studies will be necessary and appropriate for each well. Sufficient flexibility in program and funding must be maintained by DOE/DGE, in order that appropriate studies and analyses can be designed for each specific well and situation.

With respect to rock samples from geothermal wells, careful consideration of the trade-offs between costs and benefits of coring are necessary. Because of the expense, coring normally is kept to a minimum; however, an appropriate balance must be struck for each hole. A possible program might include one to three cores in a wildcat hole, with more frequent coring in a hole where the objectives are to characterize and assess a reservoir and to carry out reservoir engineering studies. In all wells, however, cutting samples should be taken every 10 metres or less. Because the costs of obtaining cutting samples are negligible compared to the costs

of drilling, it is preferable to collect too often and too much rather than too seldom and too little. Surplus samples can easily be disposed of in the future, but after the well is completed it is too late to get more.

The sampling and analytical program necessary for fluid studies will differ depending on whether the drilling is in the exploration, field development, or field management stage. In the exploration stage, a series of samples of liquid and gas should be collected once sufficient flow has been established to remove drilling fluids. Analysis of the major and minor dissolved solid and gas constituents should be performed to determine the character of the brines and to apply chemical geothermometers. In the field development stage, fluid sampling should be repeated in a systematic attempt to characterize the resource, including light stable isotope analyses of water and gases. In the field management stage, monitoring should be sufficient to detect changes in fluid chemistry, which are sensitive measures of subsurface changes such as increased boiling in the formation, interference from injection water, or cold water incursion.

Recommendations

The attached table summarizes the consortium's recommendations concerning end products and strategy for efforts funded by DOE.

Members of consortium contributing to this report

R. W. Bamford, UURI
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RECOMMENDATIONS

Recommended Item	Desired End Product(s)		Strategy	
	Regional	Reservoir	Regional	Reservoir
1. Assessment of past and current studies of rocks/fluids	a) Specify and publish present understanding of regional data for use in new interpretation of reservoir data b) Identify gaps	a) Specify and publish present understanding of utility of water/rock data to exploration and evaluation b) Identify gaps	Invited participant workshop with published proceedings	
2. Surface rock and fluid sampling program	Broad-spaced samples of fresh and altered rock, vein fracture, fault material and waters in regional areas around certain geothermal areas	Detailed samples of fresh and altered rock, vein, fracture and fault material and surface and shallow water in geothermal areas of interest	Fund sampling programs	
3. Sampling of geothermal wells	Drill hole samples in areas around geothermal areas of interest	Complete suite of drill hole samples (fluid and rock) in geothermal areas of interest	Drill intermediate-depth holes for sample acquisition	Actively seek to acquire samples from DOE and other geothermal well as they are drilled
4. Acquisition of samples from existing wells drilled for oil, minerals, water, geothermal	Samples from wells-of-opportunity which meet criteria of usefulness to geothermal research		Obtain samples from American Stratigraphic, state geological surveys, past geothermal projects	
5. Analysis of rock and fluid samples	Specification of geochemical, mineralogical, and geophysical parameters of interest in geothermal research		Fund appropriately received research proposals	
6. Synthesis of studies	Better understanding of regional data for use in improved interpretation of reservoir data	Water/rock models of geothermal systems	Periodic invited-participant workshops with published proceedings	
7. Geothermal sample library	Availability to researchers of appropriately curated samples of rocks and fluids from geothermal areas		Fund at UURI	

4.3 Electrical Methods

Recommendations of the Electrical Methods Consortium, DGE/DOE

Members

F. X. Bostick, Jr.	University of Texas at Austin
A. J. Farstad	Westinghouse
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A. O. Ramo	Sun Energy Development Co.
W. R. Sill	University of Utah
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C. M. Swift, Jr.	Chevron Resources Co. (Co-Chairman)

Outline of presentation

1) Assumptions

2) Recommended research activities

Recommendations of the Electrical Methods Consortium, DGE/DOE

Assumptions

1) Accept the DGE charge (1) to assist the development of 3000 megawatts of geothermal power by 1985 and 20,000 megawatts by 2000, and (2) to improve the existing exploration and assessment technology.

2) Electrical techniques are essential for geothermal exploration and assessment. Most of the work is being done by contractors.

3) Understanding of relative effectiveness of various electrical techniques is not well documented nor widespread. The exploration divisions of many geothermal companies are not sophisticated in their use of electrical techniques; the electrical contractors are not large, financially strong operations capable of an educational effort. In particular, EM systems are not as graspable as DC resistivity and MT.

4) Costs for definitive electrical surveys are not as cheap as commonly believed.

Assumptions (cont.)

5) Present geological documentation of geothermal systems is insufficient for proper interpretation of geophysical data.

6) From industry's viewpoint, the identifiable needs are:

(A) debugged, calibrated, contractor systems
(B) interpretive confidence in data quality and models
(C) field documentation, cross checks, case histories, and comparisons
(D) a regional electrical data base

7) The importance of technological and information transfer cannot be over-emphasized. Full and consistent documentation, plus descriptive analysis, is essential. All too frequently the average user cannot reconcile two reports written by two advocates of different methods.

8) Over-prediction and prioritizing of research topics is counterproductive. It is better to respond flexibly to individual proposals addressed to solve specified problems. Competition produced by duplicative funding can be productive.

9) Appropriate policy objectives for the Division of Geothermal Energy in an electrical methods program should be:

(A) improve the state-of-the-art in electrical methods (hardware, data processing, data interpretation)
(B) disseminate case histories, and theoretical and field studies of electrical methods over documented geothermal systems
(C) establish relative resolution, advantages, limitations, and cost-effectiveness of electrical methods in geothermal exploration programs
(D) establish a regional electrical data base.

Electrical Methods Consortium, DGE/DOE

Recommended research activities

A) Exploration technology:

1) Field Surveys - to document new EM/MT instrumentation
- to compare electrical techniques at test sites such as Roosevelt, Coso, Geysers, East Mesa
- to establish a calibration site for EM/MT systems

2) Complete funded projects - field work by EM systems at CSM and LBL
- computer model collections from debugged programs

3) Modeling, with emphasis on - 2D/3D forward solutions for EM and MT
- scale model tank work for reference for 3D solutions

4) Magnetotellurics - improve data quality using error analysis and reference field
- resolve the TE/TM mode identification problem
- investigate viability of telluric-MT surveys
- organize workshop for MT experts to discuss problems

5) Electromagnetics - compare frequency-domain and time-domain approaches
- document more surveys

6) Miscellaneous - further investigation of the use and explanation of SP
- investigate uncorrelated E field noise in geothermal areas
- support resistivity measurements at higher temperature and pressure.

B) Regional electrical survey

The idea of obtaining a regional electrical data base, similar to regional maps of heat flow, Curie point depth, and teleseismic delay times, was endorsed by the consortium, in that geothermal provinces should correlate with zones of increased temperature, and hence increased conductivity, in the lower crust and upper mantle. The specific approach, however, needs further analysis. For example, a massive MT program should wait until bias error removal schemes are widely implemented and the interpreted "deep conductor" is confidently attributed to a deep conductor and not to surface resistivity inhomogeneities.

Budget

Exploration technology in electrical methods (starting FY 7~~8~~9)	± $1000K/year
Planning for regional survey (starting FY 7~~8~~9)	± $ 150K/year
Regional survey (400 sites a year) data acquisition, processing, and interpretation (starting FY 8~~0~~1) at least	± $ 800K/year

4.4 Seismic Methods

FINAL REPORT

ACTIVE and PASSIVE

SEISMIC METHODS CONSORTIUM

Division of Geothermal Energy

Department of Energy

March, 1978

Members:

Dave Butler	Microgeophysics Inc., Colorado School of Mines
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Craig Weaver (for Iyer)	U. S. Geological Survey

1. Introduction

In this report the role and the research and development objectives of active and passive seismic techniques for geothermal resource evaluation and reservoir confirmation will be identified. The status of the previous and current DOE active and passive seismic projects will be summarized. A recommended program will then be outlined.

Instead of considering each of the different active and passive methods this report will consider the utility of seismic methods in each phase of the exploration architecture leading to the exploitation of a geothermal source. In each phase of the exploration architecture there may be several seismic techniques which are applicable. However, the effectiveness of a given technique in a specific phase will vary considerably from site to site. Geothermal resources occur in a variety of environments and one must be ready to utilize a variety of techniques.

The second general comment of this consortium related to this report is that in general seismic techniques should be used earlier in the exploration program than outlined in the second draft iteration. Prior to drilling the first deep exploratory well to an objective horizon the model of the geothermal system should have been defined by a seismic survey. Once a deep exploration drilling program begins the amount of money spent on geophysical surveys should not exceed 10% of the cost of one deep well. This expenditure for additional seismic surveys would only be made if it was impossible to reach a decision concerning abandoning a prospect, which appeared to be marginally commercial.

2.0 Exploration Technology

The objective of the exploration phase is to identify and perform general reconaissance over a geothermal area. The result of this step in the geothermal exploration is to identify a prospect or prospects and reach a decision whether or not to drill. Furthermore, if the decision is to drill a deep exploratory well, the optimal location based on geophysical surveys has been identified for this well.

The first step of exploration sequence is a general literature survey of the information in the geologic and tectonic setting of the area. This can be followed up utilizing photo geology to identify the general tectonics setting. The controlling faults and volcanism can be identified from these surveys. This should be followed up with on site checks of volcanic and the structural geology of the area. The most general reconaissance geochemical or geophysical surveys should be performed next.

Existing water wells in the area should be sampled for water isotopes and thermal gradients recorded. Hydrothermal alteration around various hot springs should be noted. Passive seismic techniques should next be applied throughout the region to identify the regional seismicity and utilize teleseisms to map the gross crustal properties. The objective is to determine the in situ rock properties and thermal regime by mapping seismic velocity and attenuation variations through the crust in this area and determine variations in the depth of the Moho. The level of seismicity can be determined from the microearthquakes that are recorded in this area and a general idea of active faults also can be inferred. P-wave traveltime delays have proven to be one of the most consistent and reliable indicators of geothermal areas. While seismic attenuation is more difficult to measure, it is

a more sensitive measure of the in situ rock properties at a given location. The passive seismic network must cover approximately 10,000 km^2. The objective is to define those areas within this 100 km x 100 km region which deserve more detailed study.

Passive seismic surveys at the present time are quite expensive to perform. One problem with such surveys is the current state of instrumentation and the data analysis procedures. These procedures are labor intensive. The geophysical contractors for such surveys do not have the economic base to fund the development of new instrumentation and the research staff to develop improved analysis procedures. This should be one objective of the Department of Energy's geothermal program.

After the reconaissance surveys have been completed a decision must be made whether there are any prospects, covering approximately 100 km^2 or less worth further exploration. Should such prospects be found the following additional geological and geophysical surveys should be performed. These include drilling and logging heat flow gradient holes together with geologic sampling and detailed seismic surveys. Seismic surveys on this scale may be either active or passive. Active seismic surveys include recording multiple coverage seismic reflection surveys to map detailed structure of the area as well as fluid content and to obtain a measure of seismic attenuation and velocity anomalies. A fan type refraction survey can be acquired simultaneously with a seismic reflection survey by "piggy-backing" on the source of the reflection survey. The seismic attenuation and velocity anomalies are direct measures of the in situ rock properties within the geothermal system. The utilization of true amplitude recording may also permit the mapping of the fluid content in the reservoirs. This information

if obtainable will be definitive for determining the optimal well placement. In certain areas active seismic surveys may not be effective, or it may be preferable to run passive surveys.

Passive seismic surveys on this scale should be conducted in a manner very similar to a reflection survey with station spacing no greater than one kilometer. They should cover the area of 100 km^2. Prior to conducting a detailed survey it has been determined that the area is seismically active improving the chances of recording many microseisms during the survey. A detailed P-wave traveltime delay survey using teleseisms can be acquired at the same time that microearthquakes are recorded. The microearthquakes will permit the determination of the velocity and attenuation structure within the area. This information is the key to determining in situ rock properties. One advantage of a passive seismic survey is that microearthquakes generate shear waves quite efficiently. It is much more difficult to generate shear waves in a reflection survey. This permits the measuring of Poisson's ratio as well. These surveys are recorded in a manner very similar to an active seismic reflection survey in terms of station spacing, station array geometry and recording dynamic range and digitization requirements. There are two other uses of a passive seismic survey. The microearthquakes can be located to define the active tectonics within the region. In addition, a three-dimensional f-k spectra of the seismic background noise can be computed. If the seismic source generates P-waves then it can be located (no seismic P-wave sources have been identified to date, McEvilly). If the seismic background noise is in the surface wave mode, these can be used to infer earth structure. At each stage in the exploration program modelling is performed. Each survey produces an improved (hopefully) idea of the geologic setting.

The seismic survey will be supplemented by a resistivity survey or an electromagnetic survey to map the thermal regime within the region. This should correlate well with the velocity anomaly, the attenuation anomalies and the variation in Poisson's ratio mapped within the geothermal system. Each of these is a measure of the in situ rock properties associated with thermal anomaly. At the end of these surveys a major decision point is reached at which time one decides to drill or not to drill. If the decision is made to drill a deep exploratory well to an objective horizon, the location for this well must be apparent.

3.0 Reservoir Assessment

In the reservoir assessment stage additional seismic surveys will rarely be performed. By the time one reaches this stage in the exploration program a decision has been made to drill a deep exploratory well and the location is well known. Assuming that such a well is drilled there are the three following possible outcomes. (1) A geothermal producer is drilled, (2) a very cold noncommercial reservoir is drilled, (3) a borderline high temperature, marginally commercial reservoir is drilled, which probably does not have adequate flow. Only in the third case would additional seismic surveys be justified. In this situation it must be determined whether the reservoir was missed or whether drilling a few feet away would intersect a fracture zone. No more than 10-20% of the cost of the deep exploratory well can be expended on additional drilling or geophysical surveys to reach a decision on whether to plug and abandon this well. At this point a few short, specific seismic reflection lines might be useful. This would aid in defining the direction for additional whip stock drilling to try to intersect fracture zones within the area. Should this prove unsuccessful, the prospect would be abandon.

If a geothermal producer is drilled and the prospect is going to be developed, then a drill rig will be leased on a long term basis and a drilling program is entered. Within this drilling program several wells will be placed and drilled in sequence. If a nonproductive geothermal well is drilled which greatly modifies the conceptional model for the geothermal system, then it would be in order to perform additional detailed seismic surveys to try and clarify the geological setting of this geothermal system. Once the drilling program is entered you move from reservoir assessment stage to the reservoir confirmation phase of the geothermal exploration.

4.0 Reservoir Confirmation

The objective of the reservoir confirmation is to define the limits of the geothermal system by deep drilling. As additional wells are drilled the utility of the geophysical surveys run previously declines because you obtain much more specific information on the subsurface from these wells. The only geophysical work performed during this stage of the development is to reinterpret the geophysical surveys in light of the additional wells to better define the model for the geothermal system.

5.0 Review of Previous and Current Seismic Programs

During November a seismic ground noise experiment was recorded by ENSCO under direction of Stan Laster of the University of Tulsa in the Cove Fort area of Utah. Data was obtained from a large array (1500 ft diameter) and a small array (220 ft diameter) at three sites. Six channels of data was recorded at each site. This represented approximately an eleven day field effort. While the data was recorded at all hours of the day the quietest time appeared to be around 7:00 a.m. each morning, rather than is frequently found during the early hours of the morning. Two of the sites were in Dog Valley (north of Cove Fort) while the third was in the foot hills. The two arrays in the valley were sited on an alluvium less than two miles from a north-south interstate highway. The data from the large array at one site in the valley was totally unusable. Only a brief segment of the data from the large array at the other site in the valley was usable and gave a noise peak in a faulted area north of the array. The data from the array in the foot hills was much quieter and seemed to show a consistent noise anomaly from a faulted area on several of the records. The data from the surface wave array (small array) has not been processed to date. The noisy conditions in the Cove Fort survey were due to the limited sites. It is doubtful that this experiment will be a definitive experiment on ground noise studies. An additional ambient ground noise research survey appears to be justified to provide further documentation of the utility of ground noise surveys. In any future ground noise surveys the number of recording channels should be increased from 6 to at least 15-20 and improved recording instrumentation of the type used in seismic reflection surveys should be utilized. More channels should be recorded with smaller array spacing.

The Lawrence Berkeley Laboratory under the direction of Tom McEvilly has conducted three passive seismic surveys. These surveys have been recorded in northern Nevada; the Geysers geothermal area, California; and are currently being recorded in Cerro Prieto, Mexico. These surveys differ from the classical passive seismic survey in which a few stations are recorded over a large area. Instead, they could be described as precision passive seismic surveys which have a recording geometry very similar to an active seismic reflection survey. At least 15 to 20 stations are recorded at a given time with a station spacing of 1 km of less. McEvilly has recorded stations as close together as 15 meters. In the production mode station arrays with a diameter of 440 ft are recommended and a station spacing interval of no greater than 1 km. The level of seismicity and the cultural seismic background noise level govern the recording period at a given site. A one month recording interval is usually sufficient to cover 100 km^2. The results of the surveys in Northern Nevada which were recorded in three different valleys: Grass Valley, Beowawe, and Buffalo Valley and the survey in the Geysers area have shown that most hydrothermally altered areas have locally anomalous attenuation structure, anomalous Poisson's ratio, and anomalous P-wave velocity variation. These surveys also permit the interpretation of microearthquake data to define the active faults and give the stress regime of the area. Additionally, frequency wave number analysis has been calculated on this data to determine the surface wave phase velocity and identify a deep seismic P-wave source. To date surface wave phase velocity has proven useful, but no P-wave source at depth has been recorded in the data.

The lateral variation of teleseismic P-wave traveltime delays have been

mapped across several geothermal areas by the group headed by H. M. Iyer of U. S. Geological Survey. In areas where digital quality seismic data has been acquired, a group headed by Ron Ward from the University of Texas at Dallas has mapped the lateral variation of seismic attenuation associated with the geothermal system. Significant teleseismic P-wave traveltime delay anomalies have been found in Yellowstone Geothermal Area, East Mesa Geothermal Area, Long Valley, and the Geysers. The data from the Coso Geothermal Area exhibits smaller traveltime delays than in these other systems. Data has also been acquired from the Snake River Plain and the Battle Mountain Heat Flow High and is being analyzed at the present time. The group at UTD has completed the analysis of seismic attenuation data for the Coso Geothermal Area and the Geysers Geothermal Area. Significant lateral variation of attenuation is exhibited in the Geysers Geothermal Area while the Coso Geothermal Area exhibits a less pronounced seismic attenuation anomaly. However, it is felt that the seismic attenuation anomaly exhibited in the Coso area is significant.

A quantitative interpretation of this data utilizing generalized geophysical inverse theory has only been performed in a few isolated examples. The data from Yellowstone has been inverted using the Aki inversion procedure. Work is currently underway at UT/Dallas to develop a generalized inversion procedure for the seismic attenuation observations recorded in Coso Geothermal Area and the Geysers Geothermal Area. Simultaneous inversion of traveltime delays and lateral attenuation anomalies will be performed next. Additional data from the Battle Mountain Heat Flow High and the Snake River Plain will be analyzed by this group. Investigators at Systems, Science and Software led by John Savino have recently preformed a joint inversion of Bouguer gravity data and teleseismic P-wave traveltime delays. They have interpreted this data in terms

of the lateral variation of seismic velocity and crustal thinning associated with the geothermal system. Geothermal anomalies at the earth's surface appear to occur in zones of crustal weakness and crustal thinning. There is a very high correlation exhibited between known geothermal areas and crustal thinning as exhibited by their data for the Imperial Valley, California.

The surveys conducted in the past of geothermal resource areas by the U. S. Geological Survey have been conducted on a regional basis to evaluate the potential of these areas. In view of the high correlation of P-wave traveltime delay anomalies and geothermal resources more detailed surveys should be conducted at the specific sites. These passive seismic surveys should acquire teleseismic data, microearthquake data, and seismic background noise data as well. The techniques need to be applied on a much more specific basis to map nearer surface anomalies. The Division of Geothermal Energy of DOE should encourage the development of instrumentation and data analysis procedures which lower the cost of such surveys. They should also support the development of quantitative modelling procedures to extract more unbiased information from existing and future data. The geophysical contractors offering services in the geothermal industry are quite small by comparison with geophysical contractors in the hydrothermal industry. They do not have the resources in equipment nor manpower to undertake these developments. This would hasten the discovery and confirmation of geothermal resources within the continental U.S.

6.0 Summary of Recommendations

The Division of Geothermal Energy/Department of Energy should support the acquisition and development of improved data analysis and interpretation techniques for both active and passive seismic surveys in localized prospects. The prospect dimensions should be 10 km x 10 km typically. The objective is to get better information into the public domain for the evaluation of the effectiveness of these procedures and to supplement the resources of the geophysical contractors serving the geothermal energy industry by providing improved instrumentation and data analysis procedures. The cost of such surveys must be reduced and the quanitity in terms of the number of stations recorded must be significantly increased in a given survey. Passive seismic surveys should be used in regions of known high seismicity. They should utilize a recording geometry and data acquisition instrumentation comparable to that used in seismic reflection profiling. Seismic reflection techniques should be developed to simultaneously record a multiple coverage reflection survey and a fan shaped refraction survey. This can be easily implemented by recording a stationary array utilizing the seismic source of the production reflection survey. Surveys of this type should be recorded in at least three different prospects the first year and the data and data analysis procedures made available to the geothermal energy industry. Funding for these three detailed surveys and data analysis procedures of $800K for FY 78 and FY 79. Instrumentation development would add to this cost.

Passive seismic reconaissance techniques must be developed. In the past the U. S. Geological Survey has installed telemetered seismic arrays at a cost of $5,000 per station for installation and $5,000 a year per station for operation. This cost is too great to be used in a reconaissance survey.

Procedures must be developed for leap frogging an array across an area and acquiring teleseismic P-wave data and microearthquake data simultaneously. The cost /km^2 should not be greater than \$5 /km^2. Computer based automatic detections procedures must be used for these events. This is best done in the recording step so that only the useful data is recorded. This program should be supported jointly with U.S.G.S. at \$500K/year. It is essential for the long term exploration of geothermal systems.

In view of the past support of the geothermal energy industry for ground noise surveys it is important to complete the investigation of the validity of such surveys. The current survey recorded in the Cove Fort geothermal area, Utah will not be the definitive experiment it should have been. The difficulty in gaining access to suitable recording sites has hampered this survey. The only available sites were in areas with high cultural background noise near an interstate highway. The data has only been analyzed from a large array and seems to indicate a geothermal ground noise source. However, considerably greater analysis is needed. This project should be continued at a very low level of funding to acquire data from at least one additional site (\$70K).

4.5 Reservoir Modeling

FINAL REPORT

EXPLORATION, MODELING, and RESERVOIR ASSESSMENT CONSORTIUM

February 9, 1978

Members contributing to report:

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EXPLORATION TECHNOLOGY

Geothermal exploration has acquired many techniques from the petroleum and mineral exploration industries and developed some which are unique to the geothermal industry. Basically geothermal exploration consists of measuring geochemical, geological, and geophysical parameters at the earth's surface and interpreting the results in terms of some geothermal model.

After more than twenty years of geothermal exploration in the United States our conceptual models of geothermal systems are still very crude. Present day exploration technology, to a large extent, identifies and evaluates only near surface leakage from the geothermal system. The identification and evaluation of blind portions of geothermal systems remains a large unknown. Improvement in exploration technology and the development of better conceptual geothermal models go hand in hand.

GEOTHERMAL MODELS

Models of geothermal systems as used in exploration strategy and reservoir assessment must be segregated with respect to scale and type. In terms of the geographical area of interest assigned to the University of Utah Research Institute it appears that four petrophysical models might describe the bulk of the geothermal systems:

1) Rift systems (Imperial Valley)
2) Subduction zones (Cascades)
3) Regional extension zones (Basin and Range)
4) Buried radiogenic plutons (Okannagan Highlands).

Numerical modeling of a geothermal system may provide output which will identify the nature of the data needed to define the system. The collection of such data will necessarily be controlled by exploration costs.

The basic constraints for the geothermal models should be established by use of numerical models based upon the measured geochemical, geological, and geophysical prospects of the system. At the present state-of-the-art we have cost-effective forward modeling programs for:

1) One-and two-dimensional magnetotelluric
2) Gravity
3) Magnetics
4) One- and two-dimensional electrical and electromagnetic
5) Conductive heat flow
6) Active seismic (both compressional and shear)
7) One- and two-dimensional induced polarization
8) Mixing models for geothermometry
9) One- and two-dimensional hydrology
10) Thermal infra-red
11) Surface temperature
12) Two-dimensional convective heat flow, and
13) Strain ratios.

Three-dimensional forward modeling is really needed to fully model a geothermal system. We can employ three-dimensional numerical modeling for many responses but usually the cost is prohibitive. Some empirical data may be obtained by use of scale models. Such data can be used as a validity check on the numerical approaches. Cost effective ways should be sought to allow two- and three-dimensional modeling of the following:

1) Magnetotellurics
2) Heat flow
3) Electrical and electromagnetics
4) Hydrological systems and thermal induced convection, and
5) Non-linear constraints - inverse problems.

As of the present it appears to the consortium that insufficient theory is available to permit forward modeling of:

1) Self potential
2) Seismic attenuation
3) Groundnoise, and
4) He^3/He^4 ratios.

RESERVOIR PARAMETER FROM MODEL OUTPUT

The output from geothermal modeling should provide a means of predicting reservoir parameters such as:

1) Temperature
2) Porosity
3) Permeability
4) Pressure
5) Geometry
6) Nature of fluid, and
7) Thermal conductivity.

The output from models may provide values for the following geophysical responses:

1) Density
2) Seismic velocity
3) Electrical resistivity
4) Total magnetization
5) Bulk polarizability
6) Expected earthquake locations, size, focal mechanism and recurrence relations.

Correlations between density, seismic velocity, electrical resistivity and porosity should be developed from models of proper scale and type. Likewise the correlations between seismic velocity, electrical resistivity and thermal conductivity should be refined.

A considerable amount of work is needed on the inverse problems connected to whole modeling input/output area. Use of mutual constraint procedures may answer many of the inverse problems.

STATISTICAL MODELING

Pattern recognition and Bayesian statistics should be applied in geothermal exploration.

Pattern recognition may find application in the search for "blind" geothermal systems. The assumption is made that all geophysical outputs previously discussed pertain to targets with some surface exposure. Then one makes the assumption that some but not all of them will be associated with blind targets. Finally the assumption is made that those associated with blind targets only will form a recognizable but yet to be determined pattern.

The Bayesian approach sifts out all output which is common to all fields or models of a given subgroup and can therefore, at this point in time, be expected to appear in the yet to be discovered members of this subgroup.

RECOMMENDATIONS

The recommendations of the consortium concerning DOE funded research in geothermal exploration, modeling and reservoir assessment are given in Table I and II.

TABLE I

GENERAL RECOMMENDATIONS

Recommended Task	Desired End Product	Stragegy	
1. Determine the Petrophysical Parameters needed	The physical parameters and boundary conditions required for models along with an expected range of values.	Group of geoscientists familiar with numerical modeling must establish the basic constraints required for geothermal modeling and ensure that data collection in Task 2 provides needed data.	
2. Characterization of Physical Models	Simplified representation of actual components of existing geothermal systems	a. Site Specific On site data accumulation for surface and subsurface data. to establish required model for each site.	b. Regional World-wide inventory of geothermal fields to establish simplest model consistant with constraints established in Task 1.
3. Simplified Models	Petrophysical 1. Rift system 2. Subduction system 3. Extension system 4. Buried pluton	a. Site Specific models for: 1. Rift system 2. Subduction system 3. Extension system 4. Buried pluton	b. Regional Take output from Task 2 a and b apply to the Petrophysical models and arrive at one or more general models.
4. Forward Modeling	Forward modeling programs for the site specific models defined by Task 3.	See Table II	
5. Inversion	Establish the inverse programs needed to go from geophysical observables to a real model of each site specific example or to a regional model.	See Table II	

TABLE II PRESENT STATE-OF-THE-ART IN MODELING AND AREAS OF MODEL RESEARCH

FORWARD MODELING

PETROPHYSICAL OPERATOR

	ρ	Kcd	V_p/V_s	Q	T	P	σ
ϕ	A_5	A_2	A_3	A_1	C_5	C_3	A_1
T	C_5	C_5	C_5	B_4	A_5	B_4	A_5
μ	C_5	C_4	$?_2$	C_5	C_5	B_2	C_5
P	B_3	C_5	C_5	C_5	B_2	C_5	C_5
F	C_5	$?_1$	A_2	A_1	C_5	C_3	A_4

MATRIX A

GEOPHYSICAL PARAMETERS

GEOPHYSICAL OPERATOR

	Mag.	Grav.	Act. Seis.	Heat Flow	MT	Elec.	EM
ρ		A_5	A_5				
Kcd				A_5			
σ					A_1	A_1	A_1
V_p/V_s				A_5			
J	A_5						
P						A_1	
Q				B_5			
Kcv					A_1		

MATRIX B

GEOPHYSICAL OBSERVABLES

REAL MODELS

A→C degree of correlation (Good to poor) for Matrix-B Forward model 3-D (known to unknown)

? Correlation unknown

1→5 Research needed (large to none) for Matrix-B could mean cost (Prohibitive to possible)

MATRIX C

1. Non linear constraint inversion
2. Boot strap technique
3. Simultaneous inversion
4. Extremal inversion

MATRIX D

1. Simultaneous Inversion
2. Empirical

GEOTHERMAL PARAMETERS

INVERSE PROGRAMS

Symbols used in Table II

Density	ρ	
Thermal Conductivity	K_{cd}	Conductive
	K_{cv}	Convective
Seismic Velocity	V_P	
	V_S	
Total Magnetization	J	
Electrical Conductivity	σ	
Seismic Dampening	Q	
Electrical Polarization	P	
Temperature	T	
Permeability	μ	
Porosity	ϕ	
Pressure	P	
Fluid	F	

Fy 78 IMPLEMENTATION

Research proposals should be solicited and funded for areas in Table II designated as A_1, A_2, $?_1$, and $?_2$ in Matrix A and B. Silimarly research should be initiated on the inverse problems. Funding should be as follows:

Matrix A	400K
Matrix B	400K
Matrix C & D	200K

4.6 Rock Properties

REPORT OF CONSORTIUM TO RECOMMEND ROCK PROPERTIES PROGRAMS

TO BE PRESENTED TO

THE PROGRAM REVIEW PANEL
DIVISION OF GEOTHERMAL ENERGY
DEPARTMENT OF ENERGY
MARCH 8, 1978

COMPILED BY

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FOREWORD

This report represents recommendations developed at the meeting of the Consortium to Recommend Rock Properties Programs to the Program Review Panel of the Division of Geothermal Energy/Department of Energy. The Consortium met on Wednesday, February 15, 1978 at Terra Tek in Salt Lake City, Utah. Those present at the meeting included Dr. A. F. Gangi, Texas A & M University; Mr. Sidney J. Green, Terra Tek; Mr. Courtney Isselhardt, Republic Geothermal; Dr. Arfon H. Jones, Terra Tek (Chairman); Mr. Steve Lipman, Union Oil Company; Dr. Mark Mathews, Los Alamos Scientific Laboratory; Dr. Gary Olhoeft, USGS; Mr. Jacob Rudisill, Thermal Power Company; Dr. William R. Sill, University of Utah, and Mr. Terrance L. Simkin, Lawrence Berkeley Laboratory. The recommended programs and level of funding outlined below represent the consensus reached by the group during the meeting and subsequent comments received by telephone and mail.

INTRODUCTION

Development of geothermal energy from exploration, reservoir assessment, reservoir confirmation to reservoir engineering requires rock properties. Interpretation of information obtained from geophysical measurements, as well as well logging tools, requires the availability of laboratory measured physical properties obtained under simulated *in situ* conditions. Such data, in conjunction with geophysical information, could provide essential reservoir engineering parameters, namely, the permeability and available porosity of the reservoir. In addition, laboratory data could be useful for the design of and interpreting output from tools designed to monitor changes in reservoir properties during production. Laboratory tests at simulated *in situ* conditions are vital to designing geothermal stimulation techniques and essential to predicting the magnitude of the resource and any surface subsidence that might accompany development of the geothermal reservoir.

Since the conditions of laboratory measurements must closely simulate the reservoir environment, parameters which should be considered independent variables in relevant experiments include at least the overburden stress, confining pressure, pore pressure, reservoir fluid chemistry, and temperature. At present, laboratory measurements of physical properties at relevant geothermal reservoir conditions are either sparse or nonexistent. No complete data set in which stresses, pore fluid chemistry and temperature are varied is available.

Another shortcoming is the lack of simultaneous measurements of several physical properties on the same core. Correlations based on simultaneous measurement of several properties are essential if information on the

permeability, porosity or salinity of a geothermal reservoir is to be inferred from sonic and resistivity tools.

The Consortium was charged with recommending programs and budgets to support the DGE geothermal source evaluation, reservoir assessment, reservoir confirmation, reservoir engineering and environmental evaluation programs. Considerations were given to:

- Defining rock properties needed in support of these elements.
- Defining efforts needed to obtain the required rock properties.
- Recommending time for initiating the identified programs.
- Listing priorities.
- Estimating the benefits of the recommended work.

The following briefly summarizes the recommendations.

TABLE I

ROCK PROPERTIES FOR GEOTHERMAL EXPLORATION

Rock Properties for Exploration Interpretation	Priority
Heat Flow Technique	
Thermal Conductivity	1
Effective Porosity	1
Permeability	1
Electrical Resistivity Technique	
Electrical Conductivity	1
Density (Bulk and Grain)	1
Streaming Potential Coefficient	2
Thermoelectric Potential	3
Zeta Potential	3
Magnetic Survey Technique	
Magnetic Susceptibility	1
Density (Bulk and Grain)	1
Curie Temperature	2
Gravity Technique	
Density (Bulk and Grain)	1
Seismic Technique	
Wave Velocities (V_p and V_s)	1
Density (Bulk)	1
Attenuation	2

Parameters

Stresses (Overburden Stress, Confining Pressure & Pore Pressure)
Reservoir Fluid
Temperature
Core Variability
Electric Current Density } Limited to Electrical
Applied Current Frequency } Conductivity Measurements

TABLE II

ROCK PROPERTIES FOR GEOTHERMAL RESERVOIR ASSESSMENT

Rock Properties	Priority
Density (Bulk)	1
Porosity	1
Permeability	1
Resistivity	1
Natural Radioactivity	1
Neutron Absorption	1
Electron Density	1

Parameters

Stresses (Overburden Stress, Confining Pressure & Pore Pressure)
Reservoir Fluid
Temperature
Core Variability

TABLE III

ROCK PROPERTIES FOR GEOTHERMAL RESERVOIR CONFIRMATION, RESERVOIR ENGINEERING AND ENVIRONMENTAL STUDIES

Rock Properties	Priority
Density (Grain and Dry)	1
Effective Porosity	1
Mineralogy (Thermal History)	1
Permeability and Relative Permeability (Matrix/Fracture)	1
Elastic Moduli (including apparent Poisson Ratio)	1
Specific Heat	1
Thermal Conductivity	1
Thermal Expansion	2
Strength (including fracture & crush-up mode)	2
Grain Size Distribution	3
Capillary Pressure	3
Coefficient of Sliding Friction	3
Long Term Nonlinear Stress-Strain Relations	3

Parameters

Stresses (Overburden Stress, Confining Pressure & Pore Pressure)
Reservoir Fluid
Temperature
Core Variability
Time

TABLE IV

RECOMMENDED ROCK PROPERTIES PROGRAMS

PROGRAM	LEVEL OF EFFORT (MILLION DOLLARS)				NOTES
	FY 78	FY 79	FY 80	FY 81	
1. Development of Capabilities to Measure Rock Properties at Simulated Geothermal Reservoir Environment and Interpret Field Data					
a) New Facilities for Handling Brines	$0.25	$0.50	$0.50	--	Funded through FY 81 only.
b) Technique Developments for Temperatures in Excess of 250°C	$0.50	$1.00	$1.00	$1.00	
2. Measurement of Rock Properties for Case History Studies (12 sites)					a) Funded through FY 81 only. b) Data will be used by researchers to reinterpret original geophysical exploration data. c) Laboratory data will be available to meet other DGE program needs. d) Laboratory data will be available to assist in developing geophysical log tools.
a) Funds to Obtain Cores	All Available Cores	$0.50	$0.50	--	
b) Measure Rock Properties in Laboratory	$0.20	$2.00	$2.00	$2.00	
3. Measurement of Rock Properties for New Geothermal Prospects					a) This program should be continued to assist geothermal development. b) Laboratory data will be available for independent geophysical interpretation by researchers and industry developers. c) Laboratory data will be available to meet other DGE program needs. d) Laboratory data available to calibrate new geophysical log tools.
a) Funding Assistance for Coring	--	$0.50	$0.50	$0.50	
b) Measure Rock Properties in Laboratory	--	$0.50	$1.00	$2.00	
(Anticipated New High Priority Prospects)		(5-8)	(5-8)	(?)	
4. Data Utilization					
a) Rock Properties Data Assimilation and Dissemination	$0.10	$0.20	$0.20	$0.20	This is a continuing program to assist in geothermal development.
b) Direct Rock Properties Modeling	$0.25	$0.50	$0.50	$0.50	
TOTAL	$1.30	$5.70	$6.20	$6.20	

TABLE V
DGE AND USGS REQUIREMENTS FOR ROCK PROPERTIES IN SUPPORT OF GEOTHERMAL ENERGY DEVELOPMENT

Program Elements	Responsible Organization						
	Division of Geothermal Energy		Lawrence Berkeley Laboratory	Lawrence Livermore Laboratory	Los Alamos Scientific Laboratory	Sandia Laboratories	U. S. Geological Survey
	Direct Contracts	University of Utah Research Institute					
Exploration	X	X	X		X		X
Assessment	X	X	X		X	X	X
Confirmation	X	X	X		X	X	X
Reservoir Engineering	X	X	X	X	X		
Environmental Studies	X					X	
Subsidence			X				X
Induced Seismicity							X
Reinjection			X				

PROPOSED PROGRAMS

Rock properties required to interpret data gathered during exploration and reservoir assessment and for reservoir confirmation, for reservoir engineering, and assessment of the environmental problems, are listed in Tables I through III. In particular, laboratory determined properties are given priority ratings of 1 through 3 in descending order of importance. Priority 1 rating indicates that the material property is required to perform preliminary evaluation of the geothermal reservoir potential. For a detailed reservoir evaluation (including the interpretation of geophysical measurements and to plan reservoir management) laboratory properties delineated Priorities 2 and 3 are needed.

In all these tests the conditions of the laboratory measurement must closely simulate the reservoir environment; hence, parameters which should be considered independent variables in relevant experiments are also listed in each table. For the reservoir fluids,

density
wave velocity
viscosity
electrical conductivity
chemical composition

are considered the important characteristics. In addition, isotope age dating can provide estimates of reservoir recharge.

In providing laboratory properties the implicit assumption has been made that the laboratory measured properties correlate with *in situ* properties. Since large rock masses are naturally inhomogeneous, property measurements must be made on several cores (a minimum of three) to obtain representative formation characteristics. Even under these conditions,

laboratory tests on both intact and fractured cores may only provide guidance to interpretation of the measured *in situ* properties.

Four major rock properties program areas required for the development of geothermal energy were delineated. They are discussed below and summarized in Table IV. The Consortium noted that due to DGE's decentralized approach, and since more than one Federal Government Department is involved, (i.e., DOE and DOI), several groups have overlapping rock properties requirements in various aspects of geothermal energy development. The responsibilities for different program elements are summarized in Table V. It was recommended that a concerted effort be made to coordinate rock properties programs to avoid duplication of funding.

1. Development of Capabilities to Measure Rock Properties and Interpret Field Data

The group noted that different research specialists are presently working on different aspects of rock property measurements. Universities, government laboratories and private laboratories will be able to work on government sponsored geothermal programs. For industry geothermal development, laboratory measured physical properties work will almost exclusively be done at private laboratories to assure proprietary handling of the data and to provide a fast response. The Consortium noted that only limited private laboratory capability presently is available for measuring rock properties at simulated geothermal reservoir environments; only one such facility has the needed equipment for simulating temperatures and stresses.

With respect to rock properties needs laboratory techniques exist for measuring physical properties to temperatures of about 200° to 250°C. New techniques are required for temperatures to 350°C and possibly higher. In addition, field techniques are required to sample reservoir fluids and then to reconstruct and handle these fluids in the laboratory. Even under the most ideal conditions, there is always the question of how well laboratory data represents *in situ* properties. Continued research is required in this area.

The total funding of $4.75M is recommended through FY81 for this program.

2. Measurement of Rock Properties for Calibration of Exploration, Reservoir Assessment, Reservoir Confirmation and Reservoir Engineering through Case History Studies

One of the greatest challenges in geothermal exploration is the discovery of large, hidden, exploitable heat reservoirs where thermal manifestations at the surface are not obvious. To date, exploration has been directed primarily to areas of surface heat leakage - such as thermal springs. Calibration of geophysical techniques in zones of known geothermal interest (Case History Studies) is an essential stage to an accelerated geothermal development program. Laboratory measured physical properties will be an integral part of such studies.

The Consortium considered that a minimum of twelve prospect Case History Studies should be performed. Prospects should be selected on the bases of:

- Available exploration, reservoir assessment, reservoir confirmation and reservoir engineering data (either a government funded or a non-proprietary development).
- Available cores and access to reservoir fluids.
- Reservoir is considered a candidate for generating electricity. Direct heat prospects are to be given lower priority.

Possible case-history prospects are:

Geysers	Desert Peak
Heber	Hawaii
Roosevelt	LASL (Dry Rock) Fenton Hill
Niland	Geopressured Well 1
East Mesa	Geopressured Well 2
Brawley	New Zealand
Baca	Philippines
Raft River	

Table IV lists the funding level required to generate a complete suite of rock properties for cores from the reservoir and from the overlying formations for a total of twelve prospects over a three year period. Funding, averaging $50,000 per prospect, should be made available for obtaining cores. The program is anticipated to be complete by the end of FY81.

This program was given high priority and for lower funding, only the higher priority material properties would be determined.

3. Measurement of Rock Properties for Exploration, Reservoir Assessment, Reservoir Confirmation, Reservoir Engineering and Environmental Studies for New Geothermal Prospects

The Consortium anticipates 15 to 20 prospects will be evaluated during FY78. They consider 5 to 8 high priority prospects annually would be a

more reasonable number to consider in the near term. As such, fundings were estimated on the basis of 5 to 8 high priority prospects annually.

Initially, only material properties characterized as Priority 1 in Table I will be evaluated at these prospects. As the prospect is developed, Priorities 2 and 3 material properties will be required for each reservoir. Funding level requested is $2M annually.

Whereas the group was unanimous in their opinion that some cores will be taken at new prospects, they strongly recommended government coring assistance averaging $50,000 per prospect to assure adequate cores to meet demands for rock properties measurements.

4. Data Utilization

Rock property data determined through the Case History Studies, and for new prospects, need to be available and thoroughly documented. A data center or the use of a current geothermal energy center needs to be established to assimilate and disseminate the data to the geothermal energy community. University, government and private researchers, and industry geothermal energy developers will need access to the data in order to first formulate mathematical models describing physical properties change with change in geothermal environment and to eventually utilize all available data for reservoir evaluation. Continuous funding is recommended for these two activities; an estimated $200,000 per year for the data center and a minimum of $500,000 per year for direct rock properties modeling.

BENEFITS OF THE RECOMMENDED PROGRAMS

The Consortium delineated direct benefits to geothermal energy development from knowledge of rock properties. These benefits included:

- Reduce Development Costs; A realistic reservoir model based on measured rock properties will result in fewer confirmation wells. At present six to seven well minimum required for reservoir confirmation may possibly be reduced by one-half to satisfactorily predict reservoir life to potential utility customers.

- Reduce Lead Time to Commercial Production; Detailed rock properties will allow more realistic reservoir modeling. With realistic models, procedures for optimizing the exploitation of a geothermal resource can be evaluated with respect to some stated criteria, e.g., maximum profit, maximum energy recovery, etc., thereby accelerating development.

- Environmental Requirements; Rock properties are necessary to evaluate the potential of subsidence, unsatisfactory induced seismicity, and to assess reinjection on reservoir performance.

True cost benefit in terms of reduced direct costs, reduced lead time and contributions to environmental requirements will be evaluated with increasing experience in geothermal energy development.

It is difficult to assess the indirect cost benefit of laboratory physical properties on (i) better interpretation of geophysical measurements in the discovery of a large, hidden, exploitable heat reservoir where thermal manifestations at the surface are not obvious, and (ii) the derivation of useful empirical correlations of rock and fluid properties for well log analyses. Nevertheless, rock properties will be required to aid developments in these areas.

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4.7 Igneous Processes

Preliminary Report of the Consortium on
Igneous Processes and Geothermal Energy

The contents of this report are based upon written and telephone communications between members of the consortium; a comprehensive document will be developed following a meeting of the whole consortium. Our initial findings are presented here in outline.

1.0 Introduction

The primary objectives of igneous studies in the geothermal program are the classification, characterization, and evaluation of volcanic systems. Field reconnaissance, mapping, age dating, and petrological studies, as embodied in U.S.G.S. Circular 726, are fundamental to a regional exploration program. More detailed studies of specific areas provide the geological foundation and rationale for local exploration and assessment studies by geophysical and geochemical methods. In addition to its role in exploration, the study of certain aspects of igneous systems contributes to reservoir assessment in terms of estimating the magnitude of igneous systems, convective fluid flow around cooling plutons, and their thermal decay regime.

2.0 Exploration Objectives

2.1 Regional exploration

2.1.1 Updating and expansion of U.S.G.S. Circular 726 data base on magnitude, age and petrology of young volcanic systems.

a) Reconnaissance evaluation of young volcanic areas of the U.S.

b) Potassium-argon age dating of silicic and mafic volcanic systems (> ~40,000 years old).

c) Thermal luminescence, fission-track, and archeomagnetic dating of very young volcanic events.

2.1.2 Geochemical studies to identify silicic igneous systems of significant magnitude and residence times in the upper crust.

2.1.3 The delineation of patterns in regional tectonism which govern systematic distribution of volcanism in time as a guide to concealed heat sources; e.g., Basin and Range, Snake River Plain, Rio Grande Rift.

2.2 Exploration technology

2.2.1 Establish a more comprehensive understanding of the relationship between volcanism and geothermal resources; particularly to determine what, if any, systematic relationships exist among specific types of volcanic systems, hydrothermal systems and geothermal anomalies. Important criteria include 1) better specific guides for exploration, 2) an improved understanding of volcanic and geothermal processes, and 3) a more accurate conceptualization of magma chamber models.

2.2.2 Case histories of established volcanic systems with proven or highly probable geothermal potential.

3.0 <u>Reservoir Assessment</u>

3.1 Magnitude of igneous systems.

Igneous studies can contribute to reservoir assessment by estimating the size of individual igneous systems. Methods include:

a) Geological control, particularly areal extent.

b) Geochemical modeling.

c) Multiple data sets from petrology, age data and heat flow.

d) Thermodynamics of magma systems, particularly mineralogical indicators of temperatures and pressures (depths) of present or past magma chambers.

3.2 Thermal decay models for igneous systems depend upon igneous temperature data, fluid dynamic characteristics of magma bodies, and the effects of convective fluid flow around cooling plutons.

4.0 Recommended areas for continued and future effort

4.1 Continued expansion of data base on distribution, age and petrology of igneous systems as embodied in U.S.G.S. Circular 726. This is a primary initial exploration method which should be closely coupled with detailed regional water chemistry studies.

4.2 Detailed studies of specific areas, in conjunction with geophysical and geochemical studies, in order to develop thorough case studies. Silicic systems are of first priority, followed by mafic systems. Coordination with other research efforts is essential, with additional priority given to areas in which deep drilling is to take place.

4.3 Continued and expanded study of the geochemistry of magmatic systems is needed, together with the development of accurate models for shallow crustal magma chambers.

4.4 We need to develop a scientific rationale for establishing just how old a volcanic system can be and still represent a viable geothermal

resource. Low temperature resources may contribute significantly to the direct heat program.

4.5 Examination of fossil geothermal systems in order to understand magma dynamics, thermal histories, and convective fluid flow regimes. These studies involve petrologic and isotopic investigations.

Tentative and Preliminary Outline of Proposed Igneous Processes Programs

Level of Effort (Million Dollars)

Program	FY 79	FY 80	FY 81
Broad Regional Studies (as in Circular 726)	.25	.25	.15
Specific Site Studies	.60	.80	.90
Geochemistry & Thermodynamics of Magma Systems	.15	.20	.22
Low Temperature Systems	.20	.25	.30
Fossil Geothermal Systems	.32	.40	.50
Data Utilization: assimilation & dissemination of igneous data	.05	.10	.10
TOTAL	1.57	2.00	2.17

5.0 Program Review Panel

So as to avoid inhibiting free and open discussion, no formal transcript was made at the meeting of the Program Review Panel on March 8, 1978. The following notes, however, record salient points made by the participants.

Industrial Representative #1

1) Regional work including heat flow measurements, topographic base maps, aerial photographic bases, gravity surveys, and aeromagnetic surveys are all prime candidates for funding.

2) DOE/DGE should ensure timely release of data from its Industry-Coupled and State-Coupled Programs.

3) Many case histories should be distributed at the expense of DOE/DGE.

4) Funding of reservoir modeling should be ensured by DOE/DGE.

5) This individual concurs with the findings of the consortia.

6) DOE/DGE should take leadership in reorganizing regulations so that institutional barriers to development of geothermal energy are much reduced.

Industrial Representative #2

1) The operation of a central clearing house for all data and technology generated under the DOE/DGE program should be assured.

2) Regional studies in support of detecting areas in which convective hydrothermal systems might be located are very important.

3) Modeling of geothermal reservoirs on the basis of surface and subsurface data is essential to progress by industry.

4) Our company, while so far involved only in electric power generation from geothermal resources, is seeking opportunities to enter the direct heat appliations field.

Industrial Representative #3

1) The efforts of DOE/DGE are now complementary to those of industry. Geothermal contractor's and geothermal exploration companies are not equipped to perform the research required to back up geothermal exploration. Hence, DOE/DGE research in exploration technology fills this void.

2) I am overwhelmed by the dollars required to perform the required research, yet everything suggested is required.

3) I am concerned with selling electric power and hence am very concerned about means for establishing reservoir longevity. For this reason I would strongly support research on reservoir modeling.

4) The regional thermal drilling program is to be endorsed as a high priority item for DOE/DGE support.

5) Case studies of drilled prospects must be placed in the public domain.

6) The DOE/DGE industry-coupled program is viable.

7) I am concerned about the overlap in organizations researching some items.

8) Non-electric applications of geothermal energy ultimately may be more important than electric applications.

Industrial Representative #4

1) The industry needs DOE/DGE funded demonstration plants.

2) Flow tests of potentially productive geothermal wells are seriously restricted by regulatory problems imposed by the Conservation Division of the USGS.

3) Regional geologic maps, regional MT surveys, and regional heat flow surveys should be funded.

4) Case histories of the application of electrical methods over the world should be distributed.

5) The water/rock interaction studies need additional funding.

6) The currently available electrical methods require significant improvement before they will be of much help to industry.

7) Reflection and passive seismic methods require more emphasis.

8) More data needs to be collected which will bear on system modeling, however the budget presented by the modeling consortium is

too large.

9) The study of thermal decay times and temperatures in volcanic rocks is a good item for support.

10) The study of rock properties is endorsed provided it encompasses more basin and range sites.

11) The east-coast non-electric program should stress the application of heat pumps.

12) The loan guarantee program is essential to building a new tier of required industry (plant operators). However, reservoir longevity insurance would serve the same purpose.

Industrial Representative #5

1) The time frame for accomplishment of the recommendations of the consortia is too long.

2) Industry needs distribution of case studies of industrial exploration underway currently.

3) The expenditures, overall, recommended by the consortia are spread too far in the short term.

4) The collection of consortia reports look too much like recommendations to an NSF program.

5) Transfer of technology to industry from DOE/DGE programs is of utmost importance.

6) The national laboratories and the specially funded academic centers should be in consort with industry in providing case history documentation.

7) Only a limited number of top priority research and exploration items should be funded by DOE/DGE.

8) Potential users should be involved at the earliest possible moment in any DOE/DGE funded program of equipment design and manufacture.

9) Use the national laboratories, the national operations offices, and their prime subcontractors in a) direct solution of industry's problems, b) service to industry, c) extra efforts associated required when unusual drilling problems arise.

10) Specialty laboratories exhibiting unique capabilities should be supported by DOE/DGE.

Industrial Representative #6

1) Everything presented by the consortia chairmen and others is terribly worthwhile to industry and the total program is endorsed.

2) Industry does not currently know how to look for geothermal resources nor what tools to use in the search.

3) There is a difficult management program for DOE/DGE and its contractors in eliminating overlap and ensuring data integration. The interest here is not so much in cost reduction but in maximizing efficiency.

4) The help that is to be provided to individuals, states, corporations, etc. by DOE/DGE and its contractors should be very carefully weighed so that industry's prime job of detecting and delineating geothermal resources is preserved.

6.0 Cost-Benefit Analysis

6.1 Institutional Problems

The major problem in placing a geothermal electrical generating plant on-stream currently is the time and money spent on institutional problems, especially complying with the poorly coordinated regulations of the DOE, the EPA, the USGS, the BLM, the Forest Service, and miscellaneous state and local agencies. Given that these problems can be minimized by early coordination of activities by DOE, then the following discussion of technological problems is of paramount importance.

6.2 Technological Problems

As Industrial Representative #6 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 the potential resources exhibiting surface manifestations. When it comes to detect and delineate totally hidden geothermal resources then, obviously, we are in even worse shape.

Table 6, developed with the assistance of Bob Greider of International Energy Corporation, shows a breakdown of costs associated with proving the existence of a field capable of 200 MWe power production. Geoscience exploration costs total $6.34M while drilling costs total $9.63 M to prove the existence of a reservoir. Table 7 lists the capital costs of developing the field and installing the physical plant. The geoscience and drilling exploration costs total $16.0M. 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 reduced by improved and

less expensive exploration technology is $23.5M 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 technology. If the capital costs are correct then they represent $966 per KW. Greider advises that the range $400 to $700 per KW is more likely. Hence if we reduce capital costs to say $550 per KW, 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 considered above but it is a factor which warrants serious consideration.

Finally, if one is to raise $193M capital costs for a 200 MWe facility, then some assurance of reservoir longevity must be provided. It is here that the recommendations contained in this report can have a very significant impact. Only via exploration technology coupled with reservoir engineering can we ever hope to estimate the longevity of a reservoir.

6.3 Regional industrial stimulation strategy

If industry is to meet the DOE/DGE goals of Table 1, it requires stimulation. A very cost-effective means for accomplishing this is to develop a regional implementation plan providing sufficient incentives for industry to reach programmatic goals. This mission-oriented strategy is effected through close cooperation with state and local governments, municipal authorities and

environmental and other public interest groups, in identifying appropriate Federal initiatives that would most effectively stimulate a geothermal industry, while promoting public acceptance of its development.

The above comments are intended to provide program managers with an input for program recommendations but also they are intended to provide the Mitre Corporation with a basis for in-depth cost benefit analyses of the program areas.

TABLE 6

Statistical Investment

Exploration Objective: 200 MW field

		$Cost
Geology & Geophysics: 64 areas ($50,000)	=	3,200,000
Additional Geophy: 32 areas ($15,000)	=	480,000
Temperature holes: 24 areas ($40,000)	=	960,000
		4,640,000
Land Acquisition: 7500 acres x 29 areas @ 7.00/acre	=	1,523,000
7500 acres x 3 areas @ 70.00/acre	=	1,575,000
		3,098,000
Detailed Geology, Geochemistry, Geophysics 16 areas @ $75,000.00	=	1,200,000
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)	=	3,000,000
		10,830,000
Testing to Establish		540,000
Fault Pattern Definition		500,000
High Resolution Seismic		
Isotope Studies		
Modeling		
Environmental Studies and Associated Costs	=	300,000
TOTAL EXPLORATION GEOSCIENCE COSTS		$ 5,680,000
TOTAL EXPLORATION DRILLING COSTS		10,830,000
LAND ACQUISITION COSTS		3,098,000
ENVIRONMENTAL COSTS		300,000
TOTAL COSTS TO PROVE FIELD EXISTENCE	=	$19,908,000

TABLE 7

CAPITAL COST ESTIMATE

Hot Water Flash 200 MW Plant

	Capital Investment
Steam Production	
Wells 50 @ $0.75 M	47,500,000
Surface Gathering, Collectors, Separators, Testing $10M	
Generating Plant	100,000,000
Turbines, Condensors, Ejectors	
Buildings, Water Treatment ($25M/50MWe)	
Substations and Transmission Lines	5,000,000
Total Direct Investment	152,500,000
Contingency and Working Capital Costs (15%)	21,375,000
Exploration Costs (From Table 6)	19,368,000
Total Costs	$193,243,000

Capital Cost $966/Kw

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January 24, 1978

David N. Anderson
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Dear Dave,

Thank you for your letter of January 19, 1978. Your notion on transfer of ownership is a fascinating concept. I would ask you to expand on it, as you have time, so that we might see how it relates to our program.

It is my opinion that the direct heat applications may well exceed electric power generation in terms of energy contributed.

Utah Power and Light has a 12000 foot well at Beryl, Utah which produces 1000 gpm from 7000 feet at 300°F. That utility is keeping the well in reserve for direct heat applications. No transfer of ownership is contemplated as far as I can determine.

Kindest regards,

Stanley H. Ward
Chairman

cw

cc: Jack Salisbury
Larry Ball
(with copy of
Anderson letter)

GEOTHERMAL RESOURCES COUNCIL

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January 19, 1978

Stanley H. Ward
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Dear Stan:

I have just finished reviewing the second iteration of the DOE reservoir evaluation and conservation program which you sent to me on December 5, 1977. I am sorry about the delay and I hope this response is not too late.

Other than providing geothermal energy with tax treatment equal to that enjoyed by other sources of energy and to significantly reduce drilling costs this program, which encourages drilling, is probably the best thing that could be done to get 2000 MW on line by the year 2000.

There is, however, one item that I did not see included in the program: A specific provision that would provide for the rapid transfer of ownership and liability of exploration or development wells that have discovered large quantities of hot water but not at temperatures high enough for electrical generation. In the course of exploration probably about 60 to 80% of the successful discovery wells will not be commercial for power production but will be prime candidates for direct uses of the geothermal fluid.

Although there are many problems involved in the transfer of wells, and I am sure that it will be easer to abandon some than to pay the rig time during the transfer process; I believe that an effort such as this could eventually prove up and make available vast reserves of hot water for non-electric uses.

Yours truly,

David N. Anderson
Executive Director

DNA/dc

William M. Dolan, *President* • Claire J. Heinzelman, *Vice President* • L. H. Axtell, *Vice President*
Phil LaMori, *Vice President* • Bob Greider, *Vice President* • David Anderson, *Secretary-Treasurer*

THE UNIVERSITY OF UTAH

SALT LAKE CITY 84112

COLLEGE OF MINES AND
MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 MINERAL SCIENCE BUILDING

January 10, 1978

Mr. C. M. Bonar
Atlantic Richfield Company
North American Producing Division
Post Office Box 2819
Dallas, Texas 75221

Dear Mr. Bonar,

Thank you for your letter of January 3, 1978. We shall certainly reflect thoroughly on your comments as we prepare the next draft of our program strategy.

The notion of finding hot spots is an interesting one.

Your time, thought, and effort in helping us define a program strategy is appreciated.

Yours sincerely,

Stanley H. Ward
Chairman

SHW:mkd

cc: Dr. Jack Salisbury

AtlanticRichfieldCompany
North American Producing Division
Post Office Box 2819
Dallas, Texas 75221
Telephone 214 651 5151

January 3, 1978

Dr. Stanley H. Ward
Director, UURI-ESL
Dept. of Geology & Geophysics
University of Utah
Salt Lake City, Utah

Dear Dr. Ward:

My reaction to your letter of December 5 concerning the DOE/DGE geothermal program is that the government is becomming much too involved in the exploration thru discovery portion of the geothermal business. I think this is primarily a private enterprise domain and does not warrant the sort of government action as set forth in your letter. Therefore, I will skip questions 1 thru 5 and respond to question #6 of your letter concerning the technological problems which appear to be preventing our reaching the national goals.

In order to reach the goals set forth by DOE/DGE it will be necessary to determine with a fair degree of confidence the likely existence of the many geothermal prospects that need be identified in order to meet these goals; 1400± per DOE/DGE estimate. Such prospect potential would, I think, be determined by the existence of numerous shallow occurring hot spots of less than 10 Km depth in order to provide the required energy for the geothermal systems. As you point out on page 6 of your cover letter on the report of the geothermal workshop on electrical methods dated January, 1977, magnetotelluric anomalies are potentially attractive as indicators of such hot spot areas but that we really have yet to understand what they are; and you state further that "we are yet sufficiently bold to obtain the answer by drilling". The utilization of Curie Isotherm mapping to identify such shallow occurring hot spots likewise appears to offer promise. Therefore, it is my recommendation that the budgeted government monies for Fy 78 thru 80 be spent in the drilling of a sufficient number of both magnetotelluric and Curie Isotherm anomalies to provide a firm basis for determining their degree of reliability as indicators of shallow hot spots. As you are aware, such drilling would be expensive, scientific in nature, and not likely to be undertaken by private enterprise.

The results of such a drilling program should provide adequate statistics on which to base a conclusion regarding the likelihood of the nation reaching the geothermal power target set forth by DOE/DGE, in addition to providing specific target areas where industry could proceed to explore for the associated geothermal systems. If such work should indicate that shallow hot spots were likely to be minimal in number with little chance, therefore, of providing for the targeted power goal, it would be ill-advised for the government to spend the funds as proposed in your letter of December 5 on projects that provided little likelihood of being meaningful to the nation.

Respectfully,

CMBonar

C. M. Bonar
Manager, Geothermal Projects

CMB/jan

INTERCONTINENTAL ENERGY CORPORATION
Exploration and Production Office
7503 Marin Drive Suite 1-C
Englewood, Colorado 80110 (303) 773-0704

January 5, 1978

Dr. Stanley H. Ward
The University of Utah
Department of Geology and Geophysics
717 Mineral Science Building
Salt Lake City, Utah 84112

Dear Dr. Ward:

Your memo of December 5, 1977 asked for a review of the Task Force programs in Exploration Technology, Reservoir Assessment, and Reservoir Confirmations. The second draft of Program Strategy was attached to provide a basis for comment.

My study of the draft and the proposed program's goals produced a conflict in my mind. If the goals are taken literally as the objective, some more thinking is indicated. The goals succinctly describe 3,000 MWe by 1985 and 20,000 MWE by 2000. There is a large percentage of programmed money indicated to other objectives than the goals. Therefore, the program appears to have been splintered to offer something for another segment of support. As to your specific questions:

1. The program will address the described objectives if the priorities under 7.9 are rearranged and the money emphasis shifted from nonelectrical programs.

2. The program should serve the industry generally, not a specific company with its own parochial goals. I think it does this. Emphasis should be restructured on "State Programs". There is a whole segment of industrial interest that should be accomodated with that portion of the program. Goals should be indicated for the nonelectric.

3. On the draft copy, I have annotated comments that are changes, additions, or deletions I would make for the program to better service industry and thereby provide usefulness for the consumer.

4. See your draft attached.

5. See your draft for comments.

IEC

6. Not a question.

7. It is apparent to me that many small entrepreneurs are deeply involved in the direct heat category. Involve these people. Be careful as they are certain the large company or fastbuck artist will steal their idea before it is financed into reality.

You will find the comments within the draft more specific than these. Thank you for considering IEC's opinions on the subject.

Regards.

Very truly yours,

Bob Greider

Bob Greider
Vice President, Exploration

cm

cc: Robert L. Fuchs
R. E. Ludt
George W. Holbrook, Jr.
John W. Salisbury

SECOND ITERATION DRAFT

Program Strategy

for

Resource Evaluation & Reservoir Confirmation

of the

Division of Geothermal Energy

of the

Department of Energy

(DOE/DGE)

1.0 Introduction

The resource evaluation and reservoir confirmation portion of the DOE/DGE program may be broken down into several phases: Exploration Technology to ~~identify~~ and locate a geothermal prospect; Reservoir assessment to evaluate a prospect; Reservoir confirmation through deep drilling; and Reservoir engineering to establish the producibility of the reservoir. The role of each of these phases and its associated technical areas have been evaluated in terms of its contribution to the DOE/DGE mission as follows.

2.0 Exploration Technology

Exploration utilizes many techniques from the oil and mining industries that are not yet optimized for discovery of geothermal resources. Some techniques specific to the geothermal industry, such as isotopic and chemical prediction of subsurface temperatures from analysis of surface waters, earth-noise and microearthquakes, and heat-flow

measurements, are being evaluated for their reliability in exploration. Surface manifestations, such as hot springs, are currently being used to target geothermal systems, making exploration technology less essential in the near-term than it will be when less obvious prospects must be discovered. Ultimately, it is essential that exploration technology be improved so as to provide the many new prospects necessary to reach our mid- and far-term goals. We estimate that, after the initial cream-skimming phase, 15 prospects must be found and evaluated for every reservoir ultimately exploited for electric power. Thus, for the 20,000 Mwe of power on-line, targeted for the year 2000 perhaps 100 reservoirs are required, which implies the ~~discovery~~ location of 1500 prospects. USGS Circular 726 identified just 63 high temperature (>150°C) geothermal systems. If only one or two prospects may be identified per system, then we have a major task ahead of us to identify, say, another 1400 prospects.

3.0 Reservoir Assessment

Reservoir assessment for prospect evaluation uses many of the same techniques as does exploration (at a different level of detail), in addition to certain site-specific activities, such as active seismic surveys. Improvements in reservoir assessment are more desirable in the near-term than are improvements in exploration, considering the high cost of the reservoir confirmation that may follow. That is, geothermal model test wells now cost about $100 per foot to drill, with total well costs approaching an average of $250,000.00 for a 2500 foot test well. Test wells costing $1.5 million have recently been reported. If the cost per well or the number of wells required to identify a reservoir could be reduced by a reasonable

percentage, then large savings in front-end cost to the industry would result.

It is essential that we attempt reservoir assessment via surface, shallow subsurface, and limited deep subsurface testing. Perhaps the most significant achievements will be made by evaluating reservoir assessment techniques and/~~or~~ * strategies at a number of thoroughly documented sites.

* strategy is an integral part of technique just as tools are an integral component of technique.

4.0 Reservoir Confirmation

Reservoir confirmation, as here defined, is proof of the existence of an economically exploitable volume and temperature of hot fluid. Reservoir confirmation is essential to the establishment of reserves sufficient to support a vigorous industry and to achieve power-on-line goals. Industry drilled fewer than 30 exploratory/step-out wells in FY 77 outside The Geysers, compared to a rate of about 200 per year needed to reach the DOE/DGE near-term goal of 3,000 MWe by 1985. Costs per 5,000 foot well are probably averaging $750,000.00 and several have encountered costs twice this figure. Under ideal circumstances of a totally coupled reservoir, at least three such wells are required to confirm this reservoir. Reservoir confirmation is, therefore, a critical path item of high priority.

A crucial question to be answered here is, "Are there techniques other than drilling, or supportive of drilling, which can reduce the cost of and provide greater assurance of reservoir confirmation?" A related question of utmost importance to those who invest in electric power plant equipment is, "How do we determine the longevity of a reservoir?" We must then address ourselves to hydrological, structural, volcanic, isotopic and geochemical, ~~plus geophysical~~ (geological) modeling of the reservoir, if we are to

Geophysical techniques must be developed to identify the parameters of the model

* This is the basis of my comments in Reno. Stan

I think it is necessary to open the ~~are~~ "dry hole" contribution or "program participation" to a much wi activity than the "parochial" approach ie. Basin & Range o

attempt to provide answers to these questions. World-wide case histories on this subject evidently need documenting and distributing if we are to take advantage of the scant experience accumulated to date. Surface, shallow sub-surface, and deep sub-surface information are all utilized in reservoir confirmation. * It is important that initial maps (descrip of the areas be retained and not adjusted to tie the subsurf information as it is obtained. Thus the final picture can be compared with the initial - pre confirmation picture. In this manner the initial appearance a bonafide prospect is not forgotten.

5.0 Reservoir Engineering

Reservoir engineering to predict the production capacity, production scheduling, production problems, production longevity, and management of a reservoir is essential to ~~attract~~ obtain users, such as utilities, who must make substantial investments in surface facilities. Oil field reservoir engineering techniques are not directly transferable* to geothermal problems because of the dominance of fracture permeability and the typical fault control of producibility. Consequently, reservoir engineering research also is a critical path item which is, of course, in part inherent in reservoir confirmation, but depends almost entirely on information obtained downhole. * This is an opinion not fact. There are many very large oil fields that owe their commercial worth to the fracture porosity and permeabilities. All hard data work

Clearly, additional problems to be addressed in reservoir engineering include self-sealing of fractures intersected by a producing well, lifetime of a single well, recharge-discharge balance, well density, maximizing efficiency of production of a given field, field longevity, brine chemistry, multiphase flow, laminar flow optimization, non-condensible gas treatment, and many other factors. These are within the capability of today's professionals

6.0 Management and Planning Task Forces

6.1 Exploration Technology, Reservoir Assessment, Reservoir Confirmation

into reservoir prediction and management programs for geothermal producing areas have responded to such massaging. There are very few reservoir P.E.'s capable of this work. The

6.1.1 Introduction

DOE/DGE has decentralized management and planning of its programs in exploration technology, reservoir assessment and reservoir confirmation by establishing a "Management and Planning Task Force" at the University of Utah. To facilitate this task the Department of Geology and Geophysics of the University of Utah (UU/GG) and the University of Utah Research Institute have established an Earth Science Laboratory (UURI/ESL) within the latter institute.

The University of Utah holds meetings of consortia of people from industry, government, and academia to provide technical input on program planning. In addition it obtains direct written and oral input from industry and state governments concerning their preferences for federal financial assistance and it holds workshops to expose to debate the issues raised by the consortia and the direct communications. The purpose of these exercises when related to exploration technology, reservoir assessment, and reservoir confirmation is to assess the current state-of-the-art in the various geological, geochemical, and geophysical, subdisciplines and to identify specific needs for further developments where DOE/DGE support is desirable and may have substantial impact.

In developing techniques one is constantly reminded of the need for cost-effectiveness. In this respect the University of Utah stresses development of exploration, assessment and confirmation architecture suited to the various types of geothermal resources occurring in each physiographic province. Of concern here are the DOE/DGE goals of 3000 MWe by 1985 and 20,000 MWe electric by 2000 plus a significant contribution to

direct application of geothermal fluids to space heating and other non-electric uses.

The program strategy is intended to be comprehensive, reflective of the needs of its constituents, and designed to ensure a cost-effective means of reaching the ambitious goals set by DOE/DGE.

6.1.2 Flow Diagram for resource exploration, assessment, and confirmation

6.1.2.1 Exploration

To illustrate the program strategy we present in Figure 1 a modular exploration sequence which includes a carefully balanced selection of geological, geochemical, and geophysical modules for geothermal prospecting for a high temperature (>200°C) resource in the eastern Basin and Range physiographic province. Appearing early in the exploration sequence are the less expensive modules. Later on the more expensive but also more definitive modules are introduced. Estimated costs per module are indicated in Figure 1 and are explained in Table 1; debate on these estimates is welcomed. Possible exploration activities such as mercury or helium gas detection in soils, remote sensing imagery, self-potential surveys, earth-noise and microearthquake surveys, etc. do not appear in this suggested exploration sequence primarily because many people have yet to be convinced of their cost-effectiveness. Others will differ in philosophy and again debate is welcomed.

The total cost per significant high temperature prospect wrung through this exploration sequence is $375,000.00. Numerous other prospects will be discarded at significantly lower cost, presumably, but such prospects will

add to the cost of the successful prospect. How far one proceeds with any given prospect depends upon economic appraisals at every branch point as Figure 1 suggests.

The end result of any geothermal exploration sequence ought to be a preliminary conceptual model of the geothermal system. (Absolute requirement

A program of lower cost* would apply to exploration for lower temperature resources used in direct heat applications. * not necessarily
It is in this exploration phase it is recognized what the chances are that this is a low or high temps resource (potential).

6.1.2.2 Assessment

Once a preliminary conceptual model of the geothermal system has been generated, model-test drilling should be initiated if warranted. Figure 2 shows a suggested geothermal reservoir assessment flow diagram and costs while Table 2 contains the cost basis and summary of costs. The basic philosophy of this approach to reservoir assessment is drilling and logging of a shallow test well plus introduction of expensive surface techniques capable of assisting in the assessment after obtaining hard data on the subsurface rock framework and wh fill.

The output of the reservoir assessment stage is a model of the geothermal system sufficiently detailed that a reservoir confirmation program may be planned, if economically warranted.

6.1.2.3 Confirmation

One can argue about the intensity of physical endeavour required for reservoir confirmation, but one can hardly argue about the fact that a large expense is required to assure confirmation.

Figure 3 and Table 3 contain our suggested minimal confirmation program. Again, this program is only suggested and debate is welcomed on procedural and economic considerations.

6.1.2.4 Land Acquisition and Environmental Costs

No consideration has been given herein to the considerable costs of acquiring land, of providing environmental impact studies, and of institutional problems. These items are excluded solely because they lie outside the purview of this program. The information required for a bona fide environmental impact analysis can only be obtained from the 6.1.2 stages. These stages must obtain answers for stage 6.1.2.4 or the program cant proceed to a favorable conclusion.

6.2 Reservoir Engineering

Reservoir engineering research is being planned by a separate Management and Planning Task Force under the direction of the Lawrence Berkeley Laboratory. This Task Force will establish program priorities and recommend the most fruitful directions for DOE/DGE research to take and any recommendations in this area should be forwarded to Dr. Paul Witherspoon, Department of Civil Engineering, University of California, Berkeley, Berkeley, California 94720. At the same time, sufficient reservoir engineering capability has been established to provide field support for DOE/DGE well testing. # One priority is to get the word into the developers that they need to obtain useful data beyond how hot is it and how much does it flow.

A preliminary report of this Task Force is available from LBL for those interested.

7.0 DOE/DGE Programs

7.1 Reservoir Confirmation

The high priority of reservoir confirmation has led to three

DOE/DGE programs:

1. The Industry-Coupled Case Study Program consists, essentially, of sharing the cost of industry exploration and step-out wells in return for data on the reservoir. This program is designed to accelerate confirmation drilling by providing monetary incentives to industry while simultaneously distributing industry-wide the knowledge gained in cost-shared programs. The uncertainties about the nature of reservoirs and the means for their confirmation are intended to be thereby reduced. Very important.

Under this program, requests for proposals (RFP's) are announced to which industry is invited to submit proposals. These proposals are submitted to technical and cost-benefit analysis and the better proposals are converted to contracts. Specific criteria under which proposals are judged are as follows. The priorities shown below are a good example of wanting to appease political goals. Be careful in casting this in bronze. Please consider another priority shown in (

(6) 1. Location: Preference is given to locations having the greatest potential for providing data applicable to the assessment and/or confirmation of a geothermal resource.

(5) 2. Date Type: Preference is given to subsurface data and to data from promising wildcat areas.

(7) 3. Contribution to DOE/DGE Goals: Preference is given to data which will most likely contribute to the DOE/DGE goals of 3,000 MWe by 1985 and 20,000 MWe by 2000. This assumes knowledge about the area that will be obtained after support not before.

(1) 4. Data Quality: Preference is given to high quality geological,

geochemical, geophysical, drilling, or reservoir test data which would most contribute to local and regional case history studies.

2 5. Data Quantity: Preference is given to proposals which offer the greatest range of data applicable to exploration technology, reservoir assessment, and reservoir confirmation.

8 6. Data Overlap: Preference is given to data which least overlaps data already in the public domain.

Continuation is more valuable if there is an existing basis in the public domain

9 7. Innovation: Preference is given to innovative approaches to exploration technology, reservoir assessment, and reservoir confirmation.

3 8. Technical Resources: Preference is given to those proposals which ensure the participation of personnel of the highest level of technical qualifications.

4 9. Schedule: Preference is given to those investigations which offer the earliest publication date.

Criteria 1, 2, and 3 are of equal importance and each carries more weight than each of the remaining criteria.

Typically, DOE/DGE will contribute 20% to 50% of the cost of the data products delivered. Some protection of proprietary data can be afforded,

but ultimately the data products must be submitted to DOE/DGE for placement in the public domain. UURI/ESL is responsible for converting the submitted data products to a reservoir case history.

2. The Pre-Commercial Case Study Program consists of a cooperative effort with the U.S. Geological Survey to confirm the existence of geothermal reservoirs, the potential of which is too speculative to attract industry. This program will, if successful, substantially contribute to the ~~number~~ location of new prospects required to reach mid- and far-term goals. It will also provide the basic resource characterization necessary to guide the development of the Hot Dry Rock Program. This is out of context.

Current activities under this program include the Cascade Volcano (Mt. Hood) project and the Hawaii project.

3. The State-Coupled Program is one designed to evaluate low and moderate temperature reservoirs for direct heat applications.* This is a cooperative effort with both the individual states and the U.S. Geological Survey. The UURI/ESL provides the Management and Planning Task Force to assist DOE/DGE in 15 western states.

When requested, the UURI/ESL will provide technical assistance to a state. Additionally, UURI/ESL serves as the liaison between the states and the National Oceanographic and Atmospheric Administration, the federal agency financed by DOE/DGE to produce descriptive maps, and summary reports thereon of the low and moderate temperature resources.

In the eastern U.S., the Virginia Polytechnical Institute (VPI) performs a function similar to that of the UURI/ESL.

Of particular concern to DOE/DGE is early establishment of milestones for energy production from low and moderate temperature reservoir (. See below)

* Why is this not considered as part of industry participation? As you know there are many industrial projects underway or in the planning and funding stage now. This offers a great

7.2 Reservoir Assessment & Exploration Technology

Research in exploration technology and reservoir assessment is also being supported. However, these are given second priority relative to reservoir confirmation at the moment because it appears that a fundamental understanding of the natures of geothermal reservoirs obtained under the confirmation programs will be at least as important as new or improved technology in these areas. However, it is in these areas that DOE/DGE particularly seeks assistance from industry, other governmental agencies, and academia in delineating and justifying particular activities which are likely to offer attractive opportunities for significant progress toward the basic goals of 3000 MWe by 1985 and 20,000 MWe by 2000. In particular, it is anticipated that exploration and assessment efforts in "wildcat" areas may require stimulus via Federal subsidy and that new exploration technology may be required for these areas. Priorities for expenditures on exploration technology, reservoir assessment, and reservoir confirmation are anticipated to change from time to time. These will change and mature slowly unless the same financial incentives are offered as thos provided other energy producing systems.

8.0 Budgetary Guidelines

For FY 78 the current plans are to distribute funds according to the following schedule.

Exploration Technology	$ 1,600K
Log Development	1,250K
Log Interpretation	800K
Reservoir Engineering Technique Development	1,650K
Reservoir Engineering Scenario Support	1,400K

applications?

6,760

Western States Nonelectric Reservoir Confirmation	3.000K *
Eastern States Nonelectric Reservoir Confirmation	3.200K
Pre-Commercial Reservoir Confirmation	2.300K
Industry-Coupled Reservoir Confirmation	3.800K
Total	$19,000K

Some flexibility in these tentative allocations exist for FY 78. Much greater flexibility exists for FY 79 and FY 80. Considering the magnitude of the problems involved, a much larger budget might be warranted and we are seeking a cost-benefit analysis of the components of the program.

* This is a good example of a bust in logic and falling for the political effect. To read 12 pgs emphasizing the objective of the program 3,000 MWe by 1985 and 20,000 MWe by 2,000, then find that as far as $ go the non electric funds are greater than the first four high priority allocations. Of the total $19 XX $8.58 M is programed for items that will not accelerate the chances for reaching the 1985 goal and most likely have little usefulness in reach yr 2,000 goal. Redefine the goals or shift more money into the next three year programs. The greatest obstacle today is having the utility users accept geothermal as an economically useful source of energy. I fail to find $ devoted to this

THE
UNIVERSITY
OF UTAH

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS

COLLEGE OF MINES AND
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717 MINERAL SCIENCE BLDG
SALT LAKE CITY, UTAH 84112

February 7, 1978

C. B. Jenkins, Manager
Geothermal Resources Division
Aminoil USA, Inc.
P.O. Box 11279
Santa Rosa, California 95406

Dear Claude,

Thank you for your thoughtful letter of January 11, 1978. When we get together on March 8, I hope that you will express your philosophical viewpoints for they are very important.

Your specific recommendations on the best method of modifying the program to attain DOE/DGE goals are sincerely appreciated. Jack Salisbury probably will want to comment on what is being done along the lines of these recommendations.

I am indeed looking forward to your participation in our March 8, 1978 Program Review Panel.

Kindest regards,

Stanley H. Ward

cc: Jack Salisbury (with copy of letter
from C. B. Jenkins)

Aminoil USA, Inc.
P. O. Box 11279
Santa Rosa, California 95406
(707) 527-5333

AMINOIL USA

January 11, 1978

Mr. Stanley H. Ward
The University of Utah
Department of Geology
and Geophysics
717 Mineral Science Building
Salt Lake City, Utah 84112

Dear Mr. Ward:

In response to your letter of December 5, 1977, it seems that I find it a little difficult to come up with the type answers you are probably looking for because of my personal reluctance to see the federal government become involved in activities which I think can more properly be handled by private industry given the proper economic/legislative support. I would be very happy to express my own philosophical views on this subject and further discuss my viewpoint on the proper role of both government and private industry in regards to energy development (especially geothermal) but don't feel that this could adequately be handled, at least by me, in this letter.

In spite of the above, we (Aminoil USA) do plan to respond on various RFP's issued by the DOE where and when Aminoil USA properties or situations appear appropriate for government participation.

Within this framework and without independent qualifications on each of our responses to your specific questions, the following comments can be made:

1) Thus far, I doubt that the program has significantly accelerated commercial geothermal development.

2) Aminoil USA has not yet directly benefited from the geothermal program.

3) See 4 below.

4) The best method of modifying the program to attain the DOE/DGE goals of 3,000 MWe by 1985 and 20,000 MWe by 2000 would be to:

   a. Accelerate the issuance of leases on geothermally promising federal owned lands.

b. Promote the passage of tax legislature which is favorable for geothermal exploration and development as well as for electric power plant construction and operation.

c. Provide resource guarantees especially to utility and perhaps even to producer if such can be done in an effective manner.

d. Assist in the promulgation of reasonable environmental restrictions and eliminate excessive and unnecessary environmental restraints.

e. Promote the acceptance of abbreviated EIR's and the development of short term EIR processing requirements by regulatory agencies.

5) The FY 78 budget split appears reasonable for the phases identified. Determination of appropriate funding levels for the various components of 4 above has not been attempted.

6) We would be glad to attend any meeting on geothermal exploration or reservoir assessments. We would also be interested in participating in any debates concerning the optimum role of government funding to expedite geothermal.

7) It appears doubtful that geothermal explorationists, in general are currently particularly interested in non-electric applications. However, should a company inadvertently discover a low to moderate temperature resource in an area where non-electrical applications may be commercial, RFP's to assist in the development of such a resource could expedite its commercial development.

I will look forward to seeing you again at future geothermal technical/administrative type meetings and hope that we will have the opportunity to further discuss this important subject of federal government involvement in geothermal development.

Yours truly,

AMINOIL USA, INC

C. B. Jenkins, Manager
Geothermal Resources Division

CBJ/rmd

THE UNIVERSITY OF UTAH

SALT LAKE CITY 84112

COLLEGE OF MINES AND
MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 MINERAL SCIENCE BUILDING

January 13, 1978

Dr. Robert W. Rex
Republic Geothermal, Inc.
11823 East Slauson Avenue, Suite One
Santa Fe Springs, CA 90670

Dear Bob,

Your thoughtful letter of January 3, 1978 has been received and is sincerely appreciated.

You have made some excellent points which we would hope to fold into our "third iteration draft".

We are, via consortia of specialists, attempting to specify the exploration techniques needed to make a technological breakthrough. These results of the consortia meetings will be reported to you later.

The DOE goals are incompletely specified by our document and these will be re-specified in our next draft: the goals for direct heat applications were not even included in our "second iteration draft".

We are, indeed, in agreement with your comment about more funding and broader selection for the "Industry Coupled Program".

You and your staff at Republic certainly are exceptionally well qualified to assist us in defining our program. It is my interest to include you or your designee in our future meetings on these matters.

Thanks, again, for helping us.

Kindest regards,

Stanley H. Ward
Chairman, UURI/ESL

CW

cc: Dr. Jack Salisbury

REPUBLIC GEOTHERMAL, INC.
11823 EAST SLAUSON AVENUE, SUITE ONE
SANTA FE SPRINGS, CALIFORNIA 90670

DR. ROBERT W. REX
PRESIDENT

(213) 945-3661

January 3, 1978

Prof. Stanley H. Ward
Department of Geology and
Geophysics
717 Mineral Science Building
University of Utah
Salt Lake City, Utah 84112

Dear Stan:

We appreciate the opportunity to comment to you on DOE's Exploration Technology, Reservoir Assessment, and Reservoir Confirmation programs that are being managed by you and your organization.

As a general comment, the "Second Iteration Draft" of the Program Strategy seems to lack focus, as it fails to clearly define the problem or describe a coordinated approach. It's difficult to see the program's early and middle-range objectives, without any evidence of milestones having yet been conceived with which to gauge and evaluate progress toward the stated goals. We're left with the feeling that a number of inherited and apparently overlapping DOE programs are simply preserved and continued, whereas a general overhaul is needed.

More specifically, the expenditure of $1.6 million for "Exploration Technology" to evaluate unspecified exploration techniques appears unlikely to produce any technological breakthroughs. New exploratory methods should be evaluated and developed, but this token level of funding offers little hope for any measurable progress to be made.

The budget item of $2.38 million for "Precommercial Reservoir Confirmation", intended to provide support to the Mt. Hood, Hawaii and Hot Dry Rock Programs, is either underfunded or unrealistically conceived if it is also intended to substantially contribute to the number of required new prospects.

The budgeting of $6.2 million (30%) for nonelectric resource confirmation is difficult to support as a cost-effective means of reaching the DOE's goals of 3,000 Mw by 1985 and 20,000 Mw by 2000. The portion for the eastern states alone is twice that budgeted for electric power oriented exploration technology. In sum, it appears that the total available funds of $19 million have been spread too thinly over too many subcategories to be very effective.

To our way of thinking, the key part of the program that has the greatest potential for getting power on line is the "Industry Coupled Reservoir Confirmation Program". Unfortunately, this program has, in our opinion, been ineffective to date. It suffers from two main defects: (1) the level of funding is too low to make much of an impact in such a high cost industry, and (2) the selection process is too restrictive, since the previous RFP limited respondents to a particular geographic area.

As you know, the bulk of 1977 funds ($4 million) went to a major oil company for the purpose of funding their drilling of a somewhat speculative prospect with decidedly specialized, if not essentially unique, problems. Even if this drilling should prove successful, the power plant construction, marketing, and transmission in that region is comparatively uncertain.

We believe the program should solicit proposals from any promising area and should select those proposals which have the greatest potential for early commercialization. By limiting proposals to a particular area, it appears that the developers who have the most extensive acreage in that area are being favored.

If we at Republic can be of any real service to you, specifically with regard to technical input meetings on program planning, please do not hesitate to let me know.

Sincerely,

JHB/JLS:eb

APPENDIX 4

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APPENDIX 5

THE
UNIVERSITY
OF UTAH

December 5, 1977

DEPARTMENT OF GEOLOGY
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COLLEGE OF MINES AND
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Z

Dear Z:

Dr. Jack Salisbury of the Division of Geothermal Energy of the Department of Energy has asked us to serve as the Management and Planning Task Force concerned with his programs in Exploration Technology, Reservoir Assessment, and Reservoir Confirmation. In this role we have the responsibility for collating advice from industry on the shaping of these programs. The attachment describes Dr. Salisbury's programs and our involvement in them. This attachment should be considered as a "straw man" which collectively we may cast in a form best suited to meet the national goals and the interests of your company. Please comment upon it or reshape it as you wish. Specific questions we wish to have answered are:

1) How well has the program served it's described objectives?

2) How well has the program served you and your company?

3) How would you modify the program to serve better the needs of your company?

4) How would you modify the program to serve better the DOE/DGE goals of 3,000 MWe by 1985 and 20,000 MWe by 2000?

5) The FY 78 budget for exploration technology, reservoir assessment, reservoir confirmation, and reservoir engineering is of order $20M. Are the monies distributed sensibly between the four categories? What level of funding and what distribution of funding between categories would you recommend for FY 79 and FY80?

6) We are conducting meetings, in the area of exploration and reservoir assessment, of consortia of specialists to identify technological problems which appear to be preventing our reaching the national goals. Other segments of DOE/DGE are addressing the institutional and environmental problems.

Additionally we are writing to you as a manager of geothermal programs to seek your advice on Federal financial involvement in geothermal exploration, assessment, and confirmation. Next, we shall hold a workshop wherein managers and specialists will be invited to debate our findings.

7) In assessing potential reservoirs which fall in the non-electric (direct heat) category, we are working with State agencies and the USGS. What involvement in direct heat applications should we seek from industry? What forums for expression of opinion should we seek in this regard?

Answering our questions may well be time-consuming for you. We apologize. We wish to help you put geothermal on stream. How can we best help you?

Kindest regards,

Stanley H. Ward
Director, UURI/ESL

cw

cc: Jack Salisbury

SECOND ITERATION DRAFT

Program Strategy

for

Resource Evaluation & Reservoir Confirmation

of the

Division of Geothermal Energy

of the

Department of Energy

(DOE/DGE)

1.0 Introduction

The resource evaluation and reservoir confirmation portion of the DOE/DGE program may be broken down into several phases: Exploration Technology to identify a geothermal prospect; Reservoir assessment to evaluate a prospect; Reservoir confirmation through deep drilling; and Reservoir engineering to establish the producibility of the reservoir. The role of each of these phases and its associated technical areas have been evaluated in terms of its contribution to the DOE/DGE mission as follows.

2.0 Exploration Technology

Exploration utilizes many techniques from the oil and mining industries that are not yet optimized for discovery of geothermal resources. Some techniques specific to the geothermal industry, such as isotopic and chemical prediction of subsurface temperatures from analysis of surface waters, earth-noise and microearthquakes, and heat-flow

measurements, are being evaluated for their reliability in exploration. Surface manifestations, such as hot springs, are currently being used to target geothermal systems, making exploration technology less essential in the near-term than it will be when less obvious prospects must be discovered. Ultimately, it is essential that exploration technology be improved so as to provide the many new prospects necessary to reach our mid- and far-term goals. We estimate that, after the initial cream-skimming phase, 15 prospects must be found and evaluated for every reservoir ultimately exploited for electric power. Thus, for the 20,000 Mwe of power on-line, targeted for the year 2000 perhaps 100 reservoirs are required, which implies the discovery of 1500 prospects. USGS Circular 726 identified just 63 high temperature (>150°C) geothermal systems. If only one or two prospects may be identified per system, then we have a major task ahead of us to identify, say, another 1400 prospects.

3.0 Reservoir Assessment

Reservoir assessment for prospect evaluation uses many of the same techniques as does exploration (at a different level of detail), in addition to certain site-specific activities, such as active seismic surveys. Improvements in reservoir assessment are more desirable in the near-term than are improvements in exploration, considering the high cost of the reservoir confirmation that may follow. That is, geothermal model test wells now cost about $100 per foot to drill, with total well costs approaching an average of $250,000.00 for a 2500 foot test well. Test wells costing $1.5 million have recently been reported. If the cost per well required to identify a reservoir could be reduced by a reasonable

percentage, then large savings in front-end cost to the industry would result.

It is essential that we attempt reservoir assessment via surface, shallow subsurface, and limited deep subsurface testing. Perhaps the most significant achievements will be made by evaluating reservoir assessment techniques and/or strategies at a number of thoroughly documented sites.

4.0 Reservoir Confirmation

Reservoir confirmation, as here defined, is proof of the existence of an economically exploitable volume of hot fluid. Reservoir confirmation is essential to the establishment of reserves sufficient to support a vigorous industry and to achieve power-on-line goals. Industry drilled fewer than 30 exploratory/step-out wells in FY 77 outside The Geysers, compared to a rate of about 200 per year needed to reach the DOE/DGE near-term goal of 3,000 MWe by 1985. Costs per 5,000 foot well are probably averaging $750,000.00 and several have encountered costs twice this figure. Under ideal circumstances of a totally coupled reservoir, at least three such wells are required to confirm this reservoir. Reservoir confirmation is, therefore, a critical path item of high priority.

A crucial question to be answered here is, "Are there techniques other than drilling, or supportive of drilling, which can reduce the cost of and provide greater assurance of reservoir confirmation?" A related question of utmost importance to those who invest in electric power plant equipment is, "How do we determine the longevity of a reservoir?" We must then address ourselves to hydrological, structural, volcanic, isotopic and geochemical, plus geophysical modeling of the reservoir if we are to

attempt to provide answers to these questions. World-wide case histories on this subject evidently need documenting and distributing if we are to take advantage of the scant experience accumulated to date. Surface, shallow sub-surface, and deep sub-surface information are all utilized in reservoir confirmation.

5.0 Reservoir Engineering

Reservoir engineering to predict the production capacity, production scheduling, production problems, production longevity, and management of a reservoir is essential to attract users, such as utilities, who must make substantial investments in surface facilities. Oil field reservoir engineering techniques are not directly transferable to geothermal problems because of the dominance of fracture permeability and the typical fault control of producibility. Consequently, reservoir engineering research also is a critical path item which is, of course, in part inherent in reservoir confirmation, but depends almost entirely on information obtained downhole.

Clearly, additional problems to be addressed in reservoir engineering include self-sealing of fractures intersected by a producing well, lifetime of a single well, recharge-discharge balance, well density, maximizing efficiency of production of a given field, field longevity, brine chemistry, multiphase flow, laminar flow optimization, non-condensible gas treatment, and many other factors.

6.0 Management and Planning Task Forces

6.1 Exploration Technology, Reservoir Assessment, Reservoir Confirmation

6.1.1 Introduction

DOE/DGE has decentralized management and planning of its programs in exploration technology, reservoir assessment and reservoir confirmation by establishing a "Management and Planning Task Force" at the University of Utah. To facilitate this task the Department of Geology and Geophysics of the University of Utah (UU/GG) and the University of Utah Research Institute have established an Earth Science Laboratory (UURI/ESL) within the latter institute.

The University of Utah holds meetings of consortia of people from industry, government, and academia to provide technical input on program planning. In addition it obtains direct written and oral input from industry and state governments concerning their preferences for federal financial assistance and it holds workshops to expose to debate the issues raised by the consortia and the direct communications. The purpose of these exercises when related to exploration technology, reservoir assessment, and reservoir confirmation is to assess the current state-of-the-art in the various geological, geochemical, and geophysical, subdisciplines and to identify specific needs for further developments where DOE/DGE support is desirable and may have substantial impact.

In developing techniques one is constantly reminded of the need for cost-effectiveness. In this respect the University of Utah stresses development of exploration, assessment and confirmation architecture suited to the various types of geothermal resources occurring in each physiographic province. Of concern here are the DOE/DGE goals of 3000 MWe by 1985 and 20,000 MWe electric by 2000 plus a significant contribution to

direct application of geothermal fluids to space heating and other non-electric uses.

The program strategy is intended to be comprehensive, reflective of the needs of its constituents, and designed to ensure a cost-effective means of reaching the ambitious goals set by DOE/DGE.

6.1.2 Flow Diagram for resource exploration, assessment, and confirmation

6.1.2.1 Exploration

To illustrate the program strategy we present in Figure 1 a modular exploration sequence which includes a carefully balanced selection of geological, geochemical, and geophysical modules for geothermal prospecting for a high temperature (>200°C) resource in the eastern Basin and Range physiographic province. Appearing early in the exploration sequence are the less expensive modules. Later on the more expensive but also more definitive modules are introduced. Estimated costs per module are indicated in Figure 1 and are explained in Table 1; debate on these estimates is welcomed. Possible exploration activities such as mercury or helium gas detection in soils, remote sensing imagery, self-potential surveys, earth-noise and microearthquake surveys, etc. do not appear in this suggested exploration sequence primarily because many people have yet to be convinced of their cost-effectiveness. Others will differ in philosophy and again debate is welcomed.

The total cost per significant high temperature prospect wrung through this exploration sequence is $375,000.00. Numerous other prospects will be discarded at significantly lower cost, presumably, but such prospects will

add to the cost of the successful prospect. How far one proceeds with any given prospect depends upon economic appraisals at every branch point as Figure 1 suggests.

The end result of any geothermal exploration sequence ought to be a preliminary conceptual model of the geothermal system.

A program of lower cost would apply to exploration for lower temperature resources used in direct heat applications.

6.1.2.2 Assessment

Once a preliminary conceptual model of the geothermal system has been generated, model-test drilling should be initiated if warranted. Figure 2 shows a suggested geothermal reservoir assessment flow diagram and costs while Table 2 contains the cost basis and summary of costs. The basic philosophy of this approach to reservoir assessment is drilling and logging of a shallow test well plus introduction of expensive surface techniques capable of assisting in the assessment.

The output of the reservoir assessment stage is a model of the geothermal system sufficiently detailed that a reservoir confirmation program may be planned, if economically warranted.

6.1.2.3 Confirmation

One can argue about the intensity of physical endeavour required for reservoir confirmation, but one can hardly argue about the fact that a large expense is required to assure confirmation.

Figure 3 and Table 3 contain our suggested minimal confirmation program. Again, this program is only suggested and debate is welcomed on procedural and economic considerations.

6.1.2.4 Land Acquisition and Environmental Costs

No consideration has been given herein to the considerable costs of acquiring land, of providing environmental impact studies, and of institutional problems. These items are excluded solely because they lie outside the purview of this program.

6.2 Reservoir Engineering

Reservoir engineering research is being planned by a separate Management and Planning Task Force under the direction of the Lawrence Berkeley Laboratory. This Task Force will establish program priorities and recommend the most fruitful directions for DOE/DGE research to take and any recommendations in this area should be forwarded to Dr. Paul Witherspoon, Department of Civil Engineering, University of California, Berkeley, Berkeley, California 94720. At the same time, sufficient reservoir engineering capability has been established to provide field support for DOE/DGE well testing.

A preliminary report of this Task Force is available from LBL for those interested.

7.0 DOE/DGE Programs

7.1 Reservoir Confirmation

The high priority of reservoir confirmation has led to three

DOE/DGE programs:

1. The Industry-Coupled Case Study Program consists, essentially, of sharing the cost of industry exploration and step-out wells in return for data on the reservoir. This program is designed to accelerate confirmation drilling by providing monetary incentives to industry while simultaneously distributing industry-wide the knowledge gained in cost-shared programs. The uncertainties about the nature of reservoirs and the means for their confirmation are intended to be thereby reduced.

Under this program, requests for proposals (RFP's) are announced to which industry is invited to submit proposals. These proposals are submitted to technical and cost-benefit analysis and the better proposals are converted to contracts. Specific criteria under which proposals are judged are as follows.

1. Location: Preference is given to locations having the greatest potential for providing data applicable to the assessment and/or confirmation of a geothermal resource.

2. Date Type: Preference is given to subsurface data and to data from promising wildcat areas.

3. Contribution to DOE/DGE Goals: Preference is given to data which will most likely contribute to the DOE/DGE goals of 3,000 MWe by 1985 and 20,000 MWe by 2000.

4. Data Quality: Preference is given to high quality geological,

geochemical, geophysical, drilling, or reservoir test data which would most contribute to local and regional case history studies.

5. Data Quantity: Preference is given to proposals which offer the greatest range of data applicable to exploration technology, reservoir assessment, and reservoir confirmation.

6. Data Overlap: Preference is given to data which least overlaps data already in the public domain.

7. Innovation: Preference is given to innovative approaches to exploration technology, reservoir assessment, and reservoir confirmation.

8. Technical Resources: Preference is given to those proposals which ensure the participation of personnel of the highest level of technical qualifications.

9. Schedule: Preference is given to those investigations which offer the earliest publication date.

Criteria 1, 2, and 3 are of equal importance and each carries more weight than each of the remaining criteria.

Typically, DOE/DGE will contribute 20% to 50% of the cost of the data products delivered. Some protection of proprietary data can be afforded,

but ultimately the data products must be submitted to DOE/DGE for placement in the public domain. UURI/ESL is responsible for converting the submitted data products to a reservoir case history.

2. The Pre-Commercial Case Study Program consists of a cooperative effort with the U.S. Geological Survey to confirm the existence of geothermal reservoirs, the potential of which is too speculative to attract industry. This program will, if successful, substantially contribute to the number of new prospects required to reach mid- and far-term goals. It will also provide the basic resource characterization necessary to guide the development of the Hot Dry Rock Program.

Current activities under this program include the Cascade Volcano (Mt. Hood) project and the Hawaii project.

3. The State-Coupled Program is one designed to evaluate low and moderate temperature reservoirs for direct heat applications. This is a cooperative effort with both the individual states and the U.S. Geological Survey. The UURI/ESL provides the Management and Planning Task Force to assist DOE/DGE in 15 western states.

When requested, the UURI/ESL will provide technical assistance to a state. Additionally, UURI/ESL serves as the liaison between the states and the National Oceanographic and Atmospheric Administration, the federal agency financed by DOE/DGE to produce descriptive maps, and summary reports thereon of the low and moderate temperature resources.

In the eastern U.S., the Virginia Polytechnical Institute (VPI) performs a function similar to that of the UURI/ESL.

Of particular concern to DOE/DGE is early establishment of milestones for energy production from low and moderate temperature reservoirs.

7.2 Reservoir Assessment & Exploration Technology

Research in exploration technology and reservoir assessment is also being supported. However, these are given second priority relative to reservoir confirmation at the moment because it appears that a fundamental understanding of the natures of geothermal reservoirs obtained under the confirmation programs will be at least as important as new or improved technology in these areas. However, it is in these areas that DOE/DGE particularly seeks assistance from industry, other governmental agencies, and academia in delineating and justifying particular activities which are likely to offer attractive opportunities for significant progress toward the basic goals of 3000 MWe by 1985 and 20,000 MWe by 2000. In particular, it is anticipated that exploration and assessment efforts in "wildcat" areas may require stimulus via Federal subsidy and that new exploration technology may be required for these areas. Priorities for expenditures on exploration technology, reservoir assessment, and reservoir confirmation are anticipated to change from time to time.

8.0 Budgetary Guidelines

For FY 78 the current plans are to distribute funds according to the following schedule.

Exploration Technology	$ 1,600K
Log Development	1,250K
Log Interpretation	800K
Reservoir Engineering Technique Development	1,650K
Reservoir Engineering Scenario Support	1,400K

Western States Nonelectric Reservoir Confirmation	3,000K
Eastern States Nonelectric Reservoir Confirmation	3,200K
Pre-Commercial Reservoir Confirmation	2,380K
Industry-Coupled Reservoir Confirmation	3,800K
Total	$19,000K

Some flexibility in these tentative allocations exist for FY 78. Much greater flexibility exists for FY 79 and FY 80. Considering the magnitude of the problems involved, a much larger budget might be warranted and we are seeking a cost-benefit analysis of the components of the program.

SUGGESTED GEOTHERMAL EXPLORATION SEQUENCE

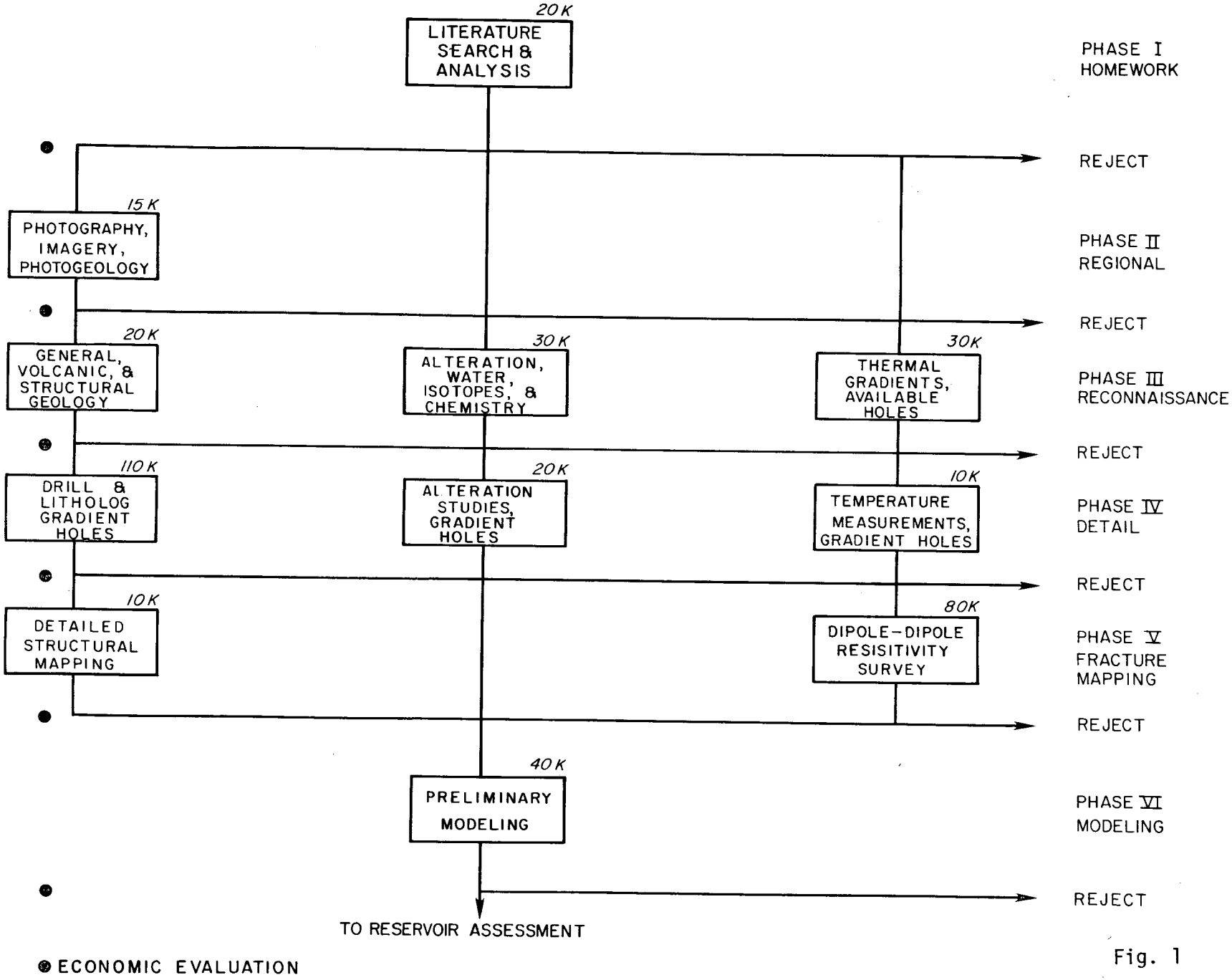

Fig. 1

SUGGESTED GEOTHERMAL RESERVOIR ASSESSMENT

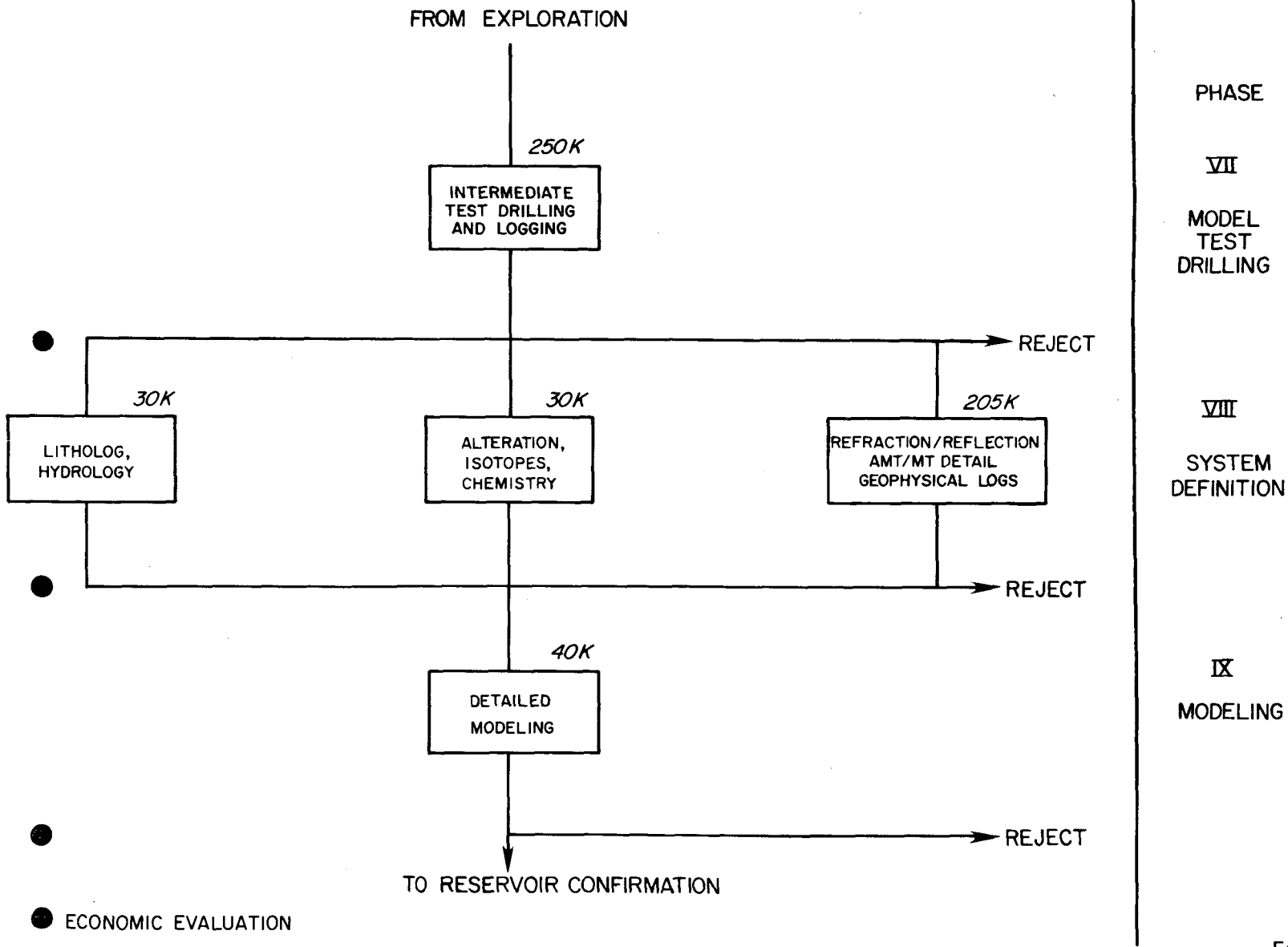

Fig. 2

SUGGESTED GEOTHERMAL RESERVOIR CONFIRMATION

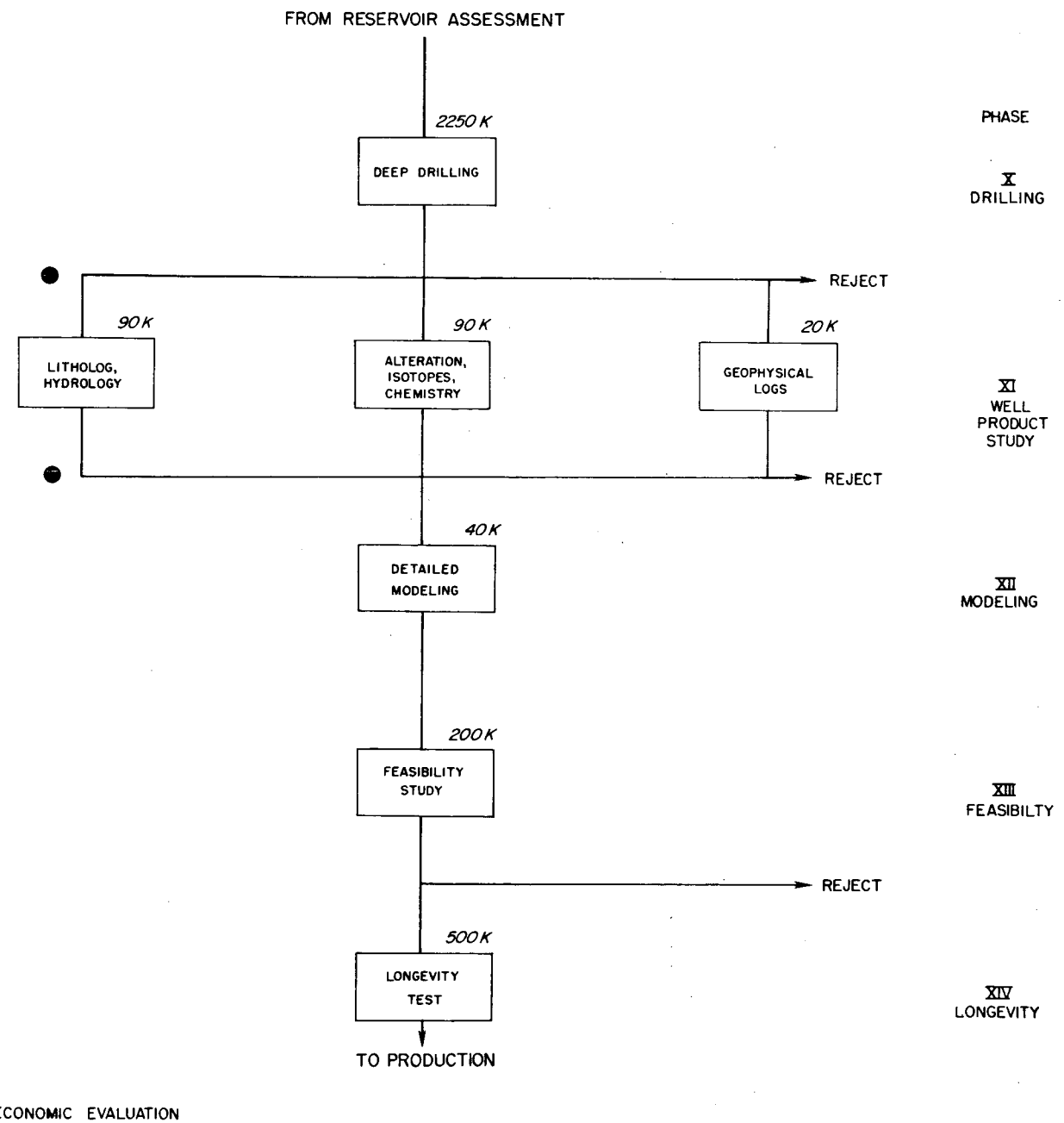

Fig. 3

TABLE 1

ESTIMATED COSTS - SUGGESTED GEOTHERMAL EXPLORATION SEQUENCE

Phase		Description	Cost per item	Cost per phase	Cost Basis	Comment
I		Literature Search & Analysis	20K	20K	0.25 Man Yr.	
II	1.	Photography, Imagery, Photogeology	15K	15K	0.10 Man Yr. +7K Data Costs	
III	1.	General, Volcanic, & Structural Geology	20K		0.25 Man Yr.	
	2.	Alteration, Water, Isotopes, & Chemistry	30K		0.25 Man Yr. +10K Analytic Costs	
	3.	Thermal Gradients, available holes	20K		0.25 Man Yr. (50 Holes)	
				70K		
IV	1.	Drill & litholog gradient holes	110K		0.25 Man Yr.	
	2.	Alteration Studies, gradient holes	20K		+90K Drilling Costs (20 Holes, cased)	
	3.	Temperature logs	10K			
				140K		
V	1.	Detailed Structural Mapping	10K		0.125 Man Yr.	
	2.	Dipole-dipole resistivity surveying	80K		48K/60 Days @800.00 + 32K Modeling & Interp.	
				90K		
VI	1.	Preliminary Conceptual Modeling	40K	40K	0.50 Man Yr.	
			Total Exploration	375K		

TABLE 2

ESTIMATED COSTS - SUGGESTED GEOTHERMAL RESERVOIR ASSESSMENT

Phase	Description	Cost per item	Cost per phase	Cost Basis	Comment
VII	Intermediate Drilling & Logging	260K	260K	2500 ft. @ $80.00/ft plus 20K logging & 0.5 Man Yr.	
VIII	System Definition				
	1. Lithology, hydrology	30K		0.25 Man Yr. + 10K analytic costs	
	2. Alteration, isotopes, chemistry	30K		0.25 Man Yr. + 10K analytic costs	
	3. Refraction/reflection seismic,	120K		80K data acquisition plus 0.50 Man Yr. interp	
	AMT/MT Detail,	60K		40K data acquisition plus 0.25 Man Yr. interp	
	Geophysical Logs	25K		11K data acquisition plus 0.10 Man Yr. interp	
			265K		
IX	Modeling		40K	0.5 Man Yr.	
		Total Reservoir Assessment	565K		

TABLE 3

ESTIMATED COSTS - SUGGESTED GEOTHERMAL RESERVOIR CONFIRMATION

Phase	Description	Cost per item	Cost per phase	Cost Basis	Comment
X	Deep Drilling		2250K	3 wells @ $750K per well to 5000 ft.	
XI	1. Litholog, hydrology	90K		0.75 Man Yr. +30K analytic cost	
	2. Alteration, isotopes, chemistry	90K		0.75 Man Yr. +30K analytic cost	
	3. Geophysical logs	20K		0.25 Man Yr. interp	
			200K		
XII	Detailed Modeling		40K	0.5 Man Yr.	
XIII	Feasibility Study		200K	2.5 Man Yr.	
XIV	Longevity Test		500K	GROSS ESTIMATE	
		Total Reservoir Assessment	$3190K		

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