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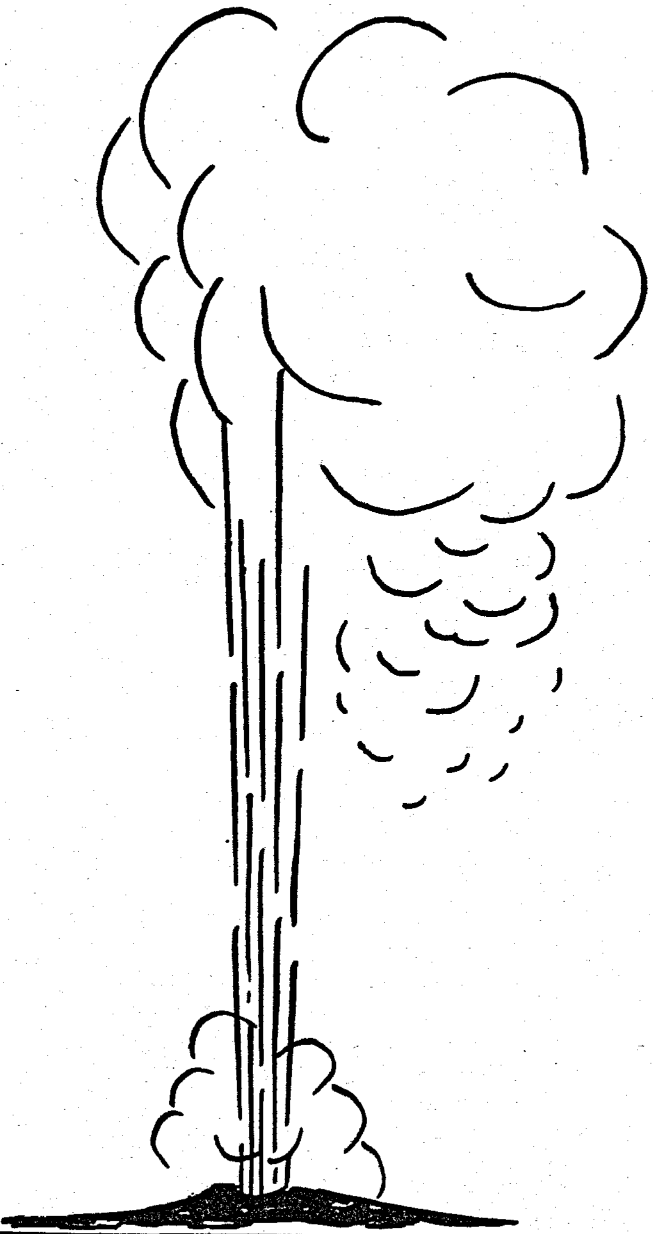

PROGRAM REVIEW—GEOTHERMAL EXPLORATION AND ASSESSMENT TECHNOLOGY PROGRAM

December 1979

Work Performed Under Contract No. AC07-79ET27002

University of Utah Research Institute
Earth Science Laboratory
Salt Lake City, Utah

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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DOE/ET/27002-6
Distribution Category UC-66a

PROGRAM REVIEW

GEOTHERMAL EXPLORATION AND ASSESSMENT TECHNOLOGY PROGRAM

Including a report of the

RESERVOIR ENGINEERING TECHNICAL ADVISORY GROUP

edited by

Dennis L. Nielson

EARTH SCIENCE LABORATORY
UNIVERSITY OF UTAH RESEARCH INSTITUTE
420 Chipeta Way, Suite 120
Salt Lake City, UT 84108

Prepared for

DEPARTMENT OF ENERGY
DIVISION OF GEOTHERMAL ENERGY
Under Contract No. DE-AC07-79ET-27002

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I. INTRODUCTION

In 1978, The Division of Geothermal Energy of the Department of Energy established the Geothermal Exploration and Assessment Technology Program. The purpose of this program is to "provide assistance to the Nation's industrial community by helping to remove technical and associated economic barriers which presently inhibit efforts to bring geothermal electric power production and direct heat application on line" (U. of Utah, Dept. of Geol. and Geophys., 1978). In the near term this involves the adaptation of exploration and assessment techniques from the mineral and petroleum industry to geothermal applications. In the near to far term it involves the development of new technology which will improve the cost effectiveness of geothermal exploration.

The success of this program must eventually be measured by an increase in the success ratio of geothermal test holes. The success ratio can be defined as the number of holes that intercept potentially commercial quantities of hydrothermal fluid divided by the total number of holes drilled. Drilling success in the past four years in the geothermal industry is shown on Figure I.1 and tabulated in Table I.1. For comparative purposes the success ratios for the oil and gas industry are also presented in Table I.1. Although the success ratio of geothermal wells drilled was quite high in 1975 and 1976, it fell off drastically in 1977 and 1978. During the same period of time the success ratio for oil and gas wells remained at a fairly constant level. The success ratio of geothermal wildcat wells is also quite low, as shown in Table I.1. Again the success ratio for oil and gas exploration wells has remained

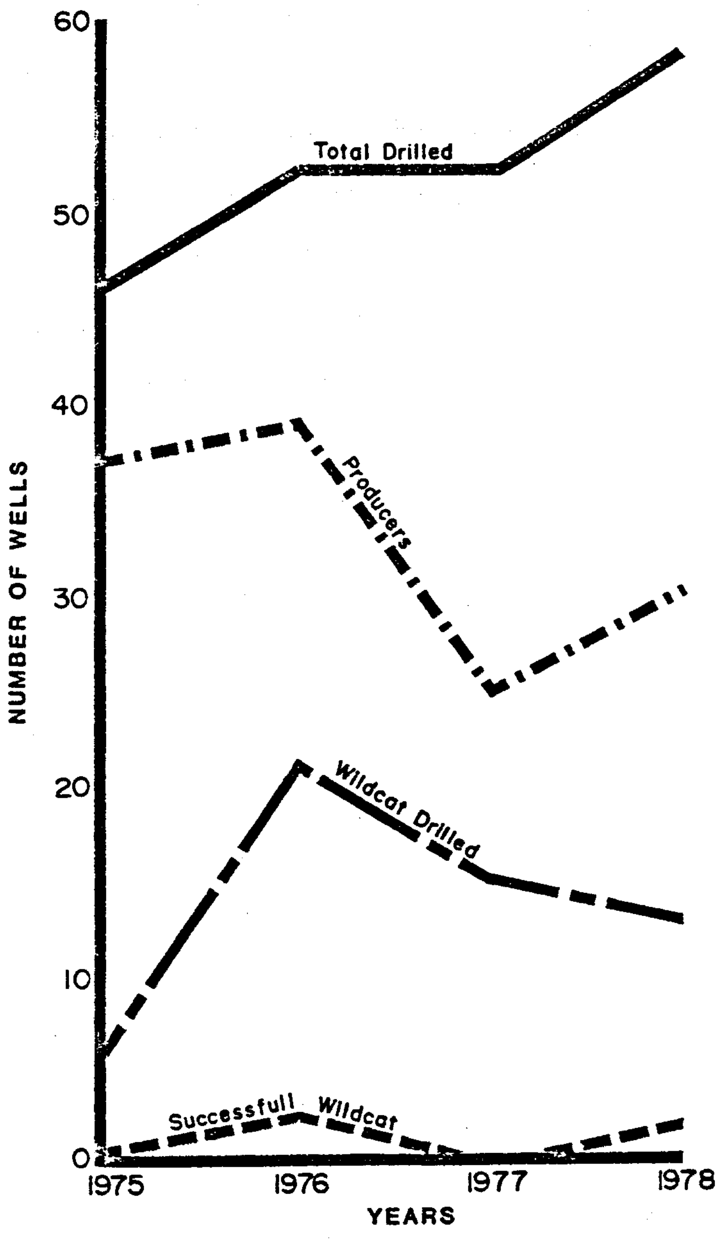

Figure I.1 Geothermal Wells Drilled (1975-1978)

TABLE I.1
Comparison of geothermal and oil and gas wells drilled
in U. S. 1975-1978

Year	Total Geothermal Wells Drilled	Producers	Success Ratio	Success Ratio Total Oil & Gas	Geothermal Wildcat Wells Drilled	Producers	Success Ratio	Success Ratio Oil & Gas Expl.
1975	46	37	.80	.644	6	1	.166	.233
1976	52	39	.75	.657	21	2-3	.95-.143	.265
1977	52	25	.38	.673	15	0	0	.270
1978	58	30	.52	.654	13	2	.154	.253

Data from: Dhillon et al., 1978; Smith and Matlick, 1976; Smith et al., 1977, 1978, 1979; and DOE/EIA, 1978.

fairly constant for the time period illustrated in Table I.1 and also for the past thirty years (DOE/EIA, 1978). Even in terms of step-out drilling in geothermal resource areas, data for 1978 (Smith et al., 1979) indicate only one successful well out of seven drilled (success ratio = .14). It can be concluded from this poor drilling success that geothermal exploration is presently at a rather immature stage of development, lagging far behind oil and gas exploration for instance. Similar conclusions have been expressed at previous meetings of geothermal experts (Ward, 1978), and can be inferred by the large variety of exploration methods being utilized by the geothermal industry (Table IV.1).

Drilling costs make up a large portion of the monies expended on geothermal exploration. Ward et al. (in press) have estimated that the exploration expense leading to the siting of a test well over a high-temperature hydrothermal convection system target in the Basin and Range is approximately $360,000. The cost of testing this target can be estimated through inspection of Figure I.2. This figure indicates that an additional expenditure of $550,000 will be required to drill a 5000 foot test well. In addition it is the opinion of Chappell et al. (1979) that drilling costs will increase exponentially as a function of depth.

Since many of the companies involved in geothermal exploration are diversified energy producers, geothermal exploration opportunities must compete with other exploration programs on the basis of return on investment. These companies will realize a return only when they are able to sell the resource. Ultimately, then, the return on investment will be tied to

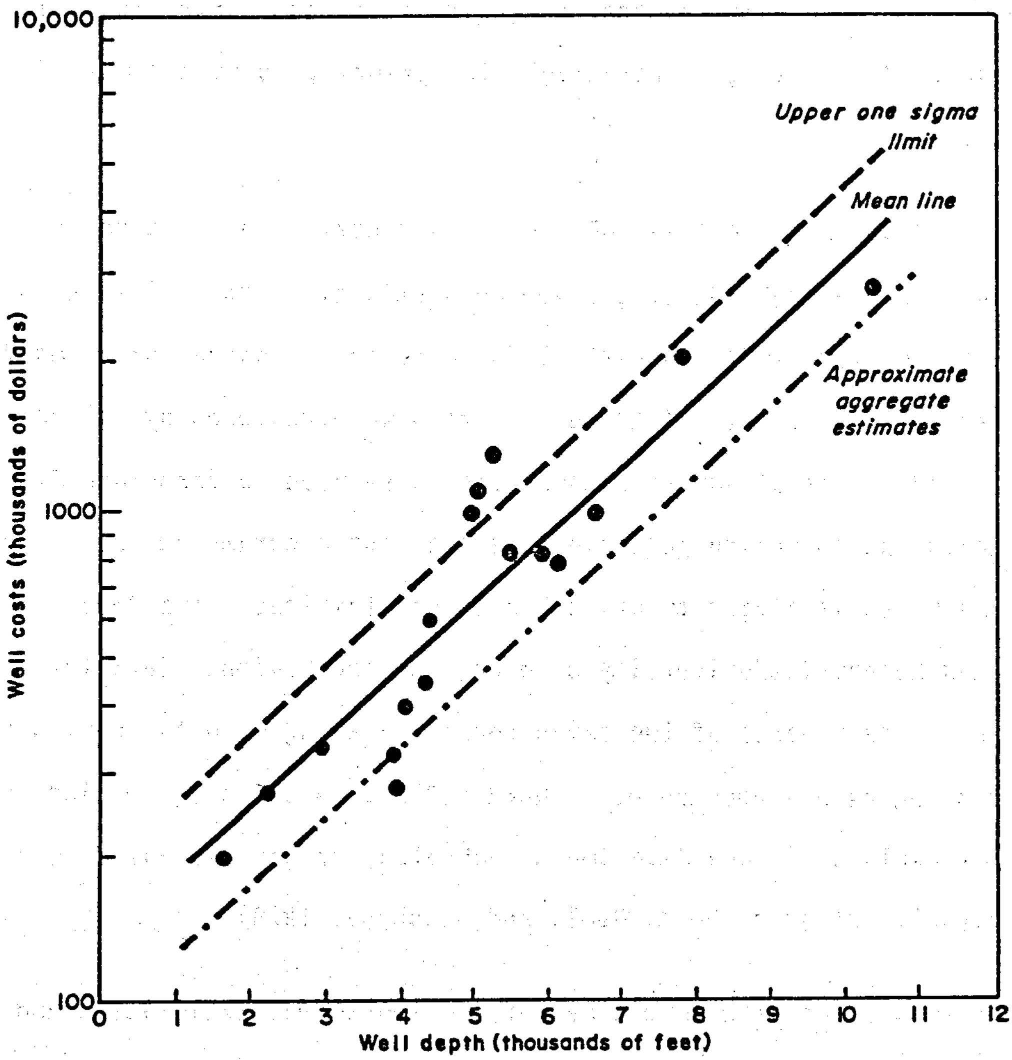

Figure I.2 - Well cost versus depth. Approximate aggregate estimate attempts to eliminate site peculiarities (Chappell, 1979).

confidence in the reservoir, which will be dependent on the assessment and reservoir engineering phases of the exploration process. With the poor success ratios shown in Table I.1 and the uncertainties associated with the assessment and engineering of the reservoir, it is not surprising that management tends to assign a relatively low priority to geothermal exploration.

In order to initiate this DOE program and define specific needs of the geothermal exploration industry, seven consortia of geothermal experts were convened during late 1977 and early 1978 to define technical problems facing the industry. The reports of these consortia were reviewed by managers from industry, and the resultant recommendations were used to formulate FY 1979 DOE procurements and to define technology development programs at the Earth Science Laboratory/University of Utah Research Institute, the Department of Geology and Geophysics/University of Utah, and the Lawrence Berkeley Laboratory. The reports of the seven consortia along with the review by industry managers are documented by Ward (1978). A DOE program plan for The Geothermal Exploration and Assessment Technology Program is based on this document (Univ. of Utah, Dept. Geol. and Geophys., 1978).

The technical review committees of the Geothermal Exploration and Assessment Technology Program are made up of experts from industry as well as academic and research institutions. There are currently six committees which cover these areas: Water/Rock Interaction; Structure, Stratigraphy, and Igneous Processes; Exploration Architecture; Electrical Methods; Seismic Methods; and Thermal Methods. These committees meet to define the state-of-the art in geothermal exploration and to recommend exploration technology development. Figure I.3 illustrates the role of these committees in defining the specific tasks of the Geothermal Exploration and Assessment Technology Program. The reports of the individual committees are contained in subsequent sections of this document.

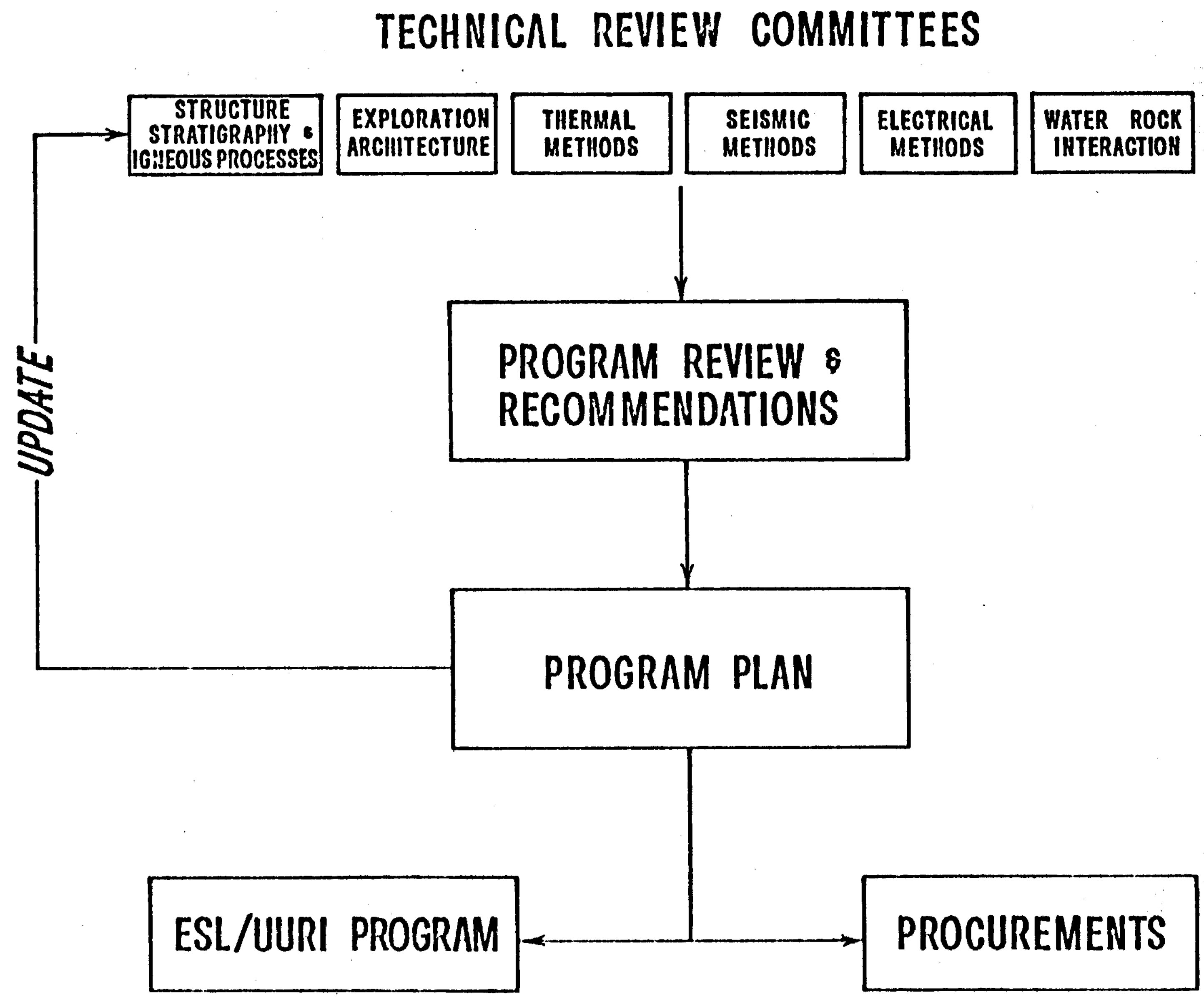

Figure I.3 - Technical Review Committee approach to task definition.

ESL/UURI provides management assistance to DOE for the Exploration and Assessment Technology Program. Table II.1 describes the projects funded by DOE pass-through monies during FY 1979. A major portion of these monies were used to fund a case studies project. This gave additional funds to fill in the data base being generated by DOE's Industry Coupled Case Studies Program. These data will be placed in the public domain as they become available. As shown in Table II.1, a large portion of the funds available have been used to test the usefulness of high resolution reflection seismic surveys in geothermal case study areas in accordance with consortia recommendations. Appropriate seismic experiments were designed based on the recommendations of three independent seismic consultants. Their recommendations resulted from an evaluation of seismic data that had already been placed in the public domain under DOE/DGE's Industry Coupled Program. Their report contains detailed recommendations on specifications of data acquisition and an evaluation of various types of surveys and is presented in Section III of this report.

TABLE II.1

Projects funded during FY 1979 under
Geothermal Exploration and Assessment Technology Program

Procurement	Company	Description
I. PRDA DE-RA07-79ET27077		
1. Borehole Geophysics	Univ. of Southern Calif. Space Sciences Inst. Los Angeles, CA	Use a borehole seismic sensor to map fracture density and orientation.
2. Multiple Geophysical Data Set Analysis	Systems, Science and Software LaJolla, CA	Perform simultaneous linear teleseismic P-wave travel times and Bouguer gravity data analyses for Roosevelt Hot Springs, Utah.
	Environmental Research Institute of Michigan Ann Arbor, MI	2-D modeling using P and S wave travel time curves, gravity, and dipole-dipole resistivity.
3. Geothermal Earth System Models	International Engineering Company (IECO) San Francisco, CA	Use case histories of Cerro Prieto, Mexico and Momotombo, Nicaragua to define most cost-effective confirmation of data for predicting reservoir parameters.
4. Geochemical Detection of Deep or Blind Parts of Hydro-thermal Systems	Barringer Research Golden, CO.	Sampling at Roosevelt Hot using conventional soil sampling techniques and a surface microlayer sampler to determine surface geochemical signature of geothermal resource.
	Earth Sciences, Inc. Golden, CO	Sulfur gas survey at Roosevelt Hot Springs, UT; East Mesa, CA., and Long Valley, CA., to assess technique as a geothermal exploration tool.
5. Analysis of 3-D inverse electrical methods	LuTech, Inc. Berkeley, CA	Use a unimoment method coupled with a finite-element and analytical expansions method to develop 3-D models.
II. RFP DE-RP07-79ID 12038	University of New Mexico Albuquerque, N.M.	Development of modeling routines to handle 3-D topographic effects in dipole-dipole and MT surveys.

III. RFP-DE-RP07-79ID 12041	Electro Magnetic Applications, Incorporated Albuquerque, N.M.	Enhancement of signal-to-noise-ratios in active source EM surveys.

IV. CASE STUDIES

Company	Amount	Area	Description
Southland Royalty Company Fort Worth, TX	$131,458	Dixie Valley, NV	Reflection seismic survey (CDP), SE-NW lines and one NE-trending tie line, totaling 16 line miles; conventional state-of-the-art processing and data display. Surface geochemical survey of approximately 30 square miles; collect and analyze about 400 soil samples for mercury and arsenic. Subsurface geochemical survey of multielement analyses of drill hole cuttings at 100 foot intervals in two 8500 foot exploratory wells. Synthesize and interpret the above data.
Union Oil Co. Rio Rancho, N.M.	$ 85,000	Stillwater, NV	Reflection seismic survey (CDP), two east-west lines and one north-south tie line, totaling about 12 line miles; either dynamite or Vibroseis sources.
Chevron Resources Company San Francisco, CA	$ 81,000	Beowawe, NV	Shallow thermal gradient hole survey, approximately 25 holes drilled to about 500 feet each. Electrical spontaneous potential survey over an area of approximately three square miles. Geochemical survey over an area of approximately two square miles; about 200 soil and/or rock samples analyzing each for mercury.

Geophysical Services, Inc. Denver, CO	$ 22,401	Roosevelt Hot Springs, UT	Reflection seismic survey data, two lines totaling 26.97 miles; Vibroseis, stacked and migrated.
AMAX Exploration Inc. Denver, CO	$ 20,000	Tuscarora, NV	Electrical resistivity (dipole-dipole) survey of about 30 line miles; two east-west lines and one north-south line. Geochemical survey along three traverse lines totaling about 30 line miles. Collect and analyze about 150 soil, stream sediment and rock samples; 50 samples for up to 15 elements; 100 samples for selective elements.
Earth Power Production, Co. Tulsa, OK	$ 18,500	Baltazor, NV	Electrical resistivity (dipole-dipole) survey, 10 line miles. Self Potential survey, approximately 10 line miles. Surface geochemical survey, approximately 500 samples, analyzing for mercury and arsenic.

III. RECOMMENDED SEISMIC SURVEYS IN CONJUNCTION WITH DOE/DGE's INDUSTRY-COUPLED PROGRAM IN THE NORTHERN BASIN & RANGE PROVINCE

S. Laster, University of Tulsa

T. V. McEvilly, University of California at Berkeley

R. Ward, University of Texas at Dallas

Background

This recommended program was formulated by the authors as consultants to UURI in a meeting held March 2-3, 1978 with UURI scientists responsible for management assistance to DOE for the Exploration and Assessment Technology and Industry Coupled Case Studies Programs. It had been determined by DOE that additional of geological/geophysical data were to be acquired as part of various contracts let by DOE in response to RFP No. ET-78-R-08-0003 for purposes of optimizing data bases in the areas under study. Some 13 individual contracts with industries were involved, with studies in progress at a number of potential geothermal fields in the Northern Basin & Range province of northern Nevada, in addition to those concerned with the Roosevelt Hot Springs and Cove Fort prospects of SW Utah.

The charge to the consulting panel, having at hand all available data for the various prospects as well as appropriate UURI experts on the areas, was as follows:

> Given the present data on the potential reservoirs represented by the DOE contracts, and the amount of about $200,000 available to acquire additional commercial seismic survey data, recommend, with priorities, specific surveys that will contribute optimally to the

case history and technology development goals of the DOE program. These goals, in the matter of seismic surveys, are further defined as providing case history data demonstrating the utility, or lack thereof, of seismic data as acquired by conventional reflection survey crews, in detecting and delineating geothermal reservoirs.

The procedure followed by the panel involved first translating the charge into a set of principles which could provide the basis for setting priorities. Next all the existing available data were reviewed, leading to a formulation of a set of general observations and comments on the utility of the method and apparent minimal requirements in its application to geothermal exploration. Finally were developed a set of surveys and locations, with priorities, recommended as optimal in potential for added knowledge through case histories on the utility of seismic reflection technology in geothermal exploration.

Priority

Consistent with the goal of adding new knowledge through case history additions the following two characteristics of a prospect are judged sufficient for assigning the highest priority for additional seismic survey coverage acquisition.

Highest Priority:

a) a prospect with high potential for becoming a successful field, but with no (or inadequate) seismic data, regardless of the amount of other geological/geophysical information existing for the area, or,

b) a more 'normal' or 'average' prospect having all other geological/geophysical data except seismic.

Other considerations for assigning priority were discussed, with two characteristics surfacing as features increasing priority in individual cases.

Other Priority Elements:

a) a unique (in terms of present knowledge) structure, or one presently unknown but suspected to be anomalous;

b) a prospect having previous seismic data judged inadequate in quantity or quality, but with moderate potential for successful completion as a reservoir.

The rules have been applied in evaluating the various prospects presented to us for consideration. Clearly each area is individual, and these elements of priority are summed as applicable for a cumulative priority in the case of specific areas.

Existing Data: General Observations and Conclusions

Reviewing all the available data on the prospects under consideration led to the following observations and conclusions.

1. State-of-the-art CDP profiling has been demonstrated to be effective in geothermal exploration, but only when the source is dynamite or VIBROSEIS (TM Continental Oil Co.).
2. Because of the inherent complexity of geothermal structures, i.e., lateral velocity changes, severe faulting, potential for much diffracted energy, etc., care must be taken in estimating velocity models in order that sections may be migrated accurately.
3. Subsurface conditions are usually 'worst case', with expected problems in static corrections and velocity variations.

4. Survey design for geothermal application should always consider the unique 'add-on' that may greatly enhance the information provided by the effort, i.e., long offsets, 2-D surface arrays for better F-K imaging, etc.

These factors have been incorporated into our recommended specifications for the surveys proposed in this report, as they are results of analyzing the data of the type sought.

Existing Seismic Data: Adequate

Available data for the Northern Basin & Range have demonstrated the utility of modern seismic reflection surveying in obtaining data allowing detailed structural and fault mapping to production depths of around 4,000 feet. Data from Leach Hot Springs and San Emidio, both structures of the range-front fault (RFF) type, i.e., potential reservoirs involving hot water circulation associated with the major boundary fault at one edge of a basin, are of excellent quality as geothermal seismic data go, with numerous coherent reflections for subsurface structure mapping. Both surveys were judged perfectly adequate in demonstrating cost-effectiveness and utility in the RFF situtation. The San Emidio survey is complete. At Leach Hot Springs there is an unmapped structure which is discussed below.

Data from Soda Lake (CDP, as opposed to the weight-drop survey) are considered adequate and useful in mapping the intra-valley basement structure and faulting associated with the potential reservoir envisioned there, but in less detail than the above two surveys. The survey is viewed as cost-effective.

Existing Seismic Data: Inadequate

In this category can fall data of two types: state-of-the-art and non-state-of-the-art. The former is the more important, with serious implications. In the data available from the Industry Coupled Case Studies Program there were no examples of modern data of the former category which were inadequate. We understand, however, that allegations to this effect have been made concerning seismic data which is not in the public domain. Unfortunately, we cannot know what criteria have been used in these assessments. The standards for a successful petroleum seismic reflection survey are more stringent than those we would set for a geothermal survey.

On the other hand, we have reviewed three data sets falling into the category of inadequate but not state-of-the-art:

--Weight-drop data at Beowawe

--Weight-drop data at Soda Lake

--Single-fold data at Cove Fort

In the first two cases, the data offer no clue as to whether or not modern CDP profiling will succeed (we know, however, that it did for the second; and we hear that it did not in the first) in the area. The single-fold data at Cove Fort, however, do indicate that multifold data acquisition should provide usable data in that area.

Existing Data: In Progress

In this category of data that will ultimately become public domain though the DOE - Industry Coupled Case Studies Program is the recently acquired Chevron data from Beowawe. Taking a more long-range view, we can consider much of the presently 'tight' data on potential fields such as Roosevelt as ultimately contributing to the case history file--but the contribution may simply come too late to provide input to the development of seismic exploration technology.

Recommendations: Survey Parameters

Barring very special conditions unique to a particular area, the panel of consultants feels that future surveys specified by DOE to contractors should meet the following general design parameters for the field procedures:

--VIBROSEIS or dynamite source

--2400% coverage

--110' group spacing

--12 geophones/group minimum

--*12-60 Hz sweeps

--*16 sweeps minimum

--*10-20 sec sweeps

--4 sec records, minimum

*VIBROSEIS crew

Processing is the key to success in the complex problem of geothermal seismic data, and a knowledgeable seismolgist must interact with those doing the processing. The minimal product from the survey must be processing through migration with the standard processing package, but with particular attention to the velocities determined and used in the migration routine. Static corrections must be treated with special care. The expenditure for data processing in a geothermal survey will be a relatively larger fraction of total cost than it is for reflection surveys in petroleum exploration.

It is vital to seismic exploration technology to evaluate the effectiveness of imaging techniques in reservoir detection, and in surveys the following field parameters should be specified as general guidelines:

--6 x 8 array, regularly spaced (48 channels minimum)

--110' intervals

--18 element geophone cross (4.5 Hz)

--location approx. 0.5-1.0 mi from surface point above expected reservoir

--large dynamic range recording system (80 dB+)

Such a modification, termed FKI here (for frequency-wavelength imaging), should be incorporated in a CDP survey in instances where we have a great deal of other geological/geophysical data, where interference from cultural sources (drilling, traffic, towns and industry) is very low, and, particularly, if we have evidence for seismic activity near the potential reservoir, though this last requirement should not preclude such a survey if the other two conditions are satisfied. The DOE program can make a substantial contribution by encouraging a few FKI surveys in appropriate situations as add-ons to CDP survyes. As an add-on such a survey is quite inexpensive.

Details of the line or array geometry in a survey will naturally depend on the particular site, although some general guidelines should be followed. These are based on the goal of demonstrating utility or lack of utility of the methods. Demonstration implies mapping capabilities for structure and faulting down to at least 4,000', in the vicinity of the suspected reservoir. Consequently, dense coverage is not needed. In most Basin & Range cases, three lines at most should suffice, with a total coverage of less than 20 line miles. Evaluation of the FKI process requires only one setup at a prospect--spectacular results will insure subsequent evaluation and DOE will have accomplished its goal.

Cost estimations:

CDP Profiling.	The above specifications of 48 points/mile will allow 1.5 to 2 miles per day, at best, for a cost, at $7500 per day (including processing), of $60K-90K for a typical 3-line (two @ 6 mi, crossed by a 4 mi line), 16 mile survey.
FKI Surveying.	As an add-on, this aspect of the field effort amounts to no more than one day's work, and consequently will add less than $10K to the total survey cost.

Recommendations: First Priority Surveys

Based on the principles set out above and the analyses of existing data for the subject prospects, we recommend the following data be acquired at DOE request by the appropriate contractor for the prospect. These three recommendations, presented in order of priority, are considered to be of the highest priority in the context of the DOE goal of optimal case history development through the addition of important and critically needed new knowledge.

1. Leach Hot Springs, Panther Canyon Site. This prospect rose to top priority for several reasons: 1) the large amount of other geological/geophysical data on hand for the area, 2) the somewhat unique structural setting of the site (on the trend intersection of the Grass Valley - Pleasant Valley offset and the regional NE-SW structural feature in the area), 3) the well defined target of high heat flow and microseismicity (somewhat unique itself in geothermal

prospects), 4) the high probability of good data based on experience to the northwest at the Leach Hot Springs itself in the same valley, 5) the opportunity to conduct also the FKI experiment, and, lastly, 6) its proximity to the second recommended area, below, and the potential for cost saving in conducting both surveys in one field operation.

The recommended survey geometry (Fig. III.1) involves two crossed 5-mile lines, intersecting about one mile SW of the target, and normal to the two dominant structural trends in the area. The FKI spread would be incorporated near the intersection of the two lines.

2. Dixie Valley. This prospect received high priority because of its status as a high potential area based on much existing data. It offers also the opportunity for a full case history on a classical (RFF) type structure. The field geometry (Fig. III.2) represents that typically found in the RFF situtation. It is important that both dip lines be shot and that they be tied by the cross line, in order that mapping quality and consistency can be ascertained and so that the data can be compared to well data. The importance of acquiring all the lines is emphasized here because the lease situation looks messy, and the tendency may be to compromise the survey. Under no circumstances should the proposed survey be reduced to less than two lines, one down-dip and a cross line in the valley east of the RFF. The details of the survey are to be as specified above for CDP profiling. FKI is not recommended for Dixie

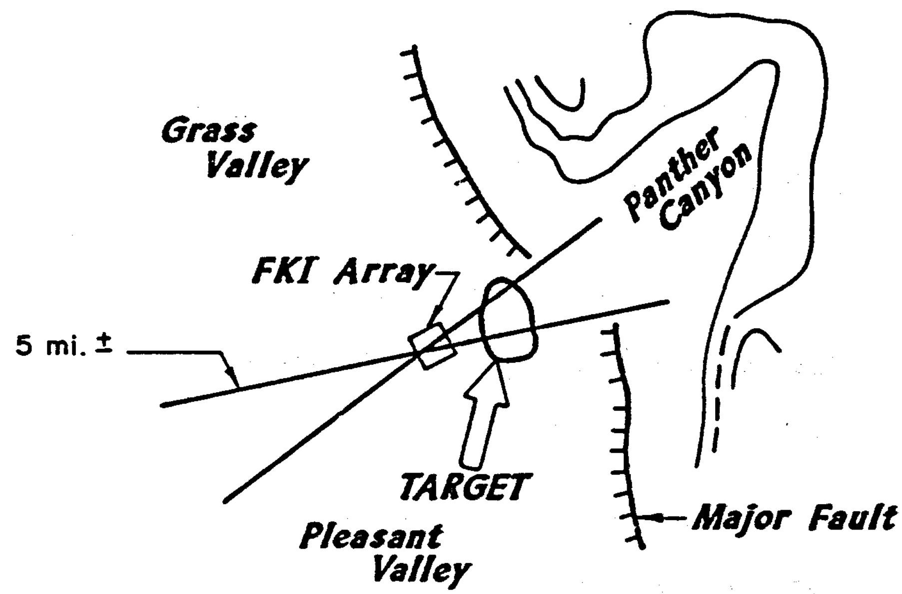

Figure III.1 Recommended Seismic Survey at Panther Canyon

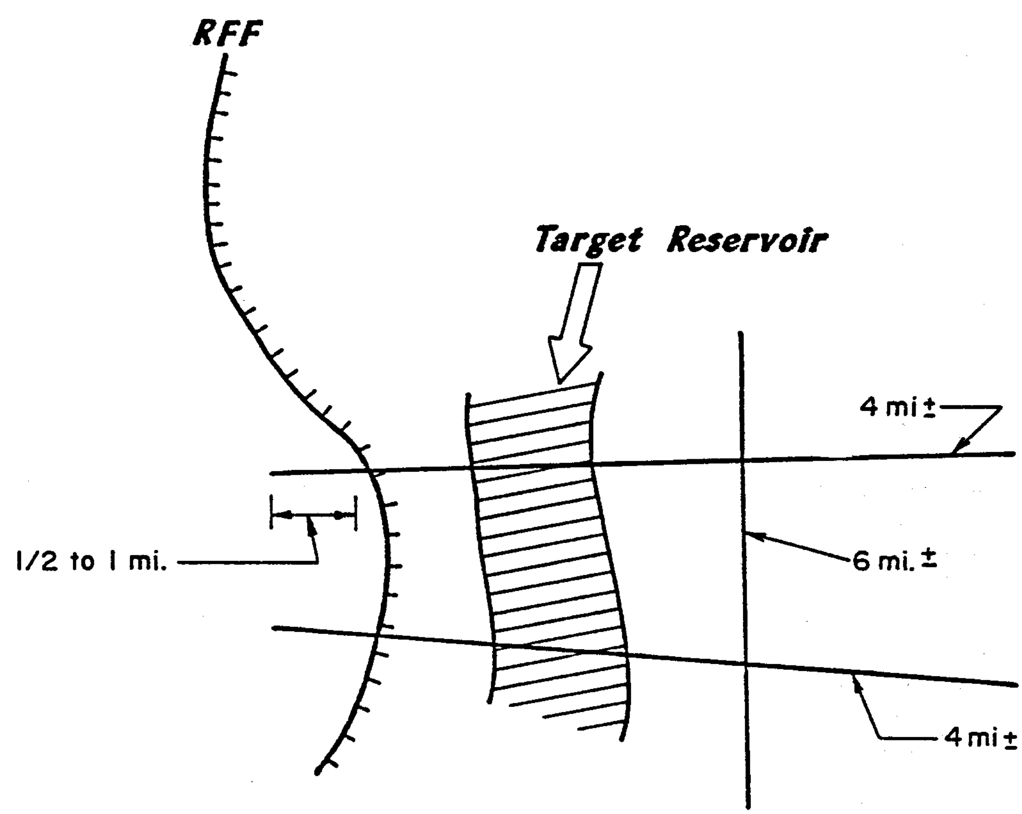

Figure III.2 Recommended Seismic Survey in Dixie Valley

Valley at this time because of interference considerations from wells. In all, the recommendation is for two 6-mile lines spaced 2 miles apart and crossed by a 4-mile line on their eastern segments.

3. Roosevelt & Cove Fort GSI Data. These data are invaluable in ascertaining the utility of seismic profiling in these unique structures. Furthermore, Roosevelt, while doubtless covered by proprietary data in the hands of Phillips, will probably become the second successful geothermal field in the nation, and, as such, should have some seismic data in the public domain.

We recommend is the acquisition by purchase of two 5-mile segments, one from each of the appropriate GSI lines. At Roosevelt, the segment would lie in sections 1-5; at Cove Fort the needed segment runs from section 25 eastward to the county line.

We cannot overemphasize the importance of these data, and stress that their acquisition through purchase is, while third priority, still in the top three priorities, far above the next choices. As such, all efforts must be made to get the data, even if quality is poor--that in itself needs to be documented publicly.

Cost Estimate for First Priority Survey Data Acquisition. We estimate the cost for the set of first priority recommendations as follows:

Leach, Panther Canyon	$45K-75K
Dixie Valley	60K-90K
Roos./C. Fort GSI data	50K-75K
TOTAL	$155K-240K

Recommendation: Second Priority Surveys

Realizing that one of the first priority recommendations may not be possible to accomplish, we selected the following course of action as a second priority alternate. It should be realized, however, that there is wide difference in the value of this acquisition and the value of any of the top three recommendations.

Stillwater-Soda Lake Joint Survey. Stillwater has interest as a unique intrabasin prospect, similar to Soda Lake. While little is presently known of the geology and structure, the acquisition of gravity, magnetic, resistivity, and shallow and deep thermal gradient data is underway prior to the drilling of two planned deep exploratory holes. We can assume similar geological settings for the two prospects and make a case for a combined survey, with emphasis on obtaining adequate data on the surface configuration of the basement volcanics.

We envision one additional line through the previously surveyed Soda Lake Area, and two lines at Stillwater as a cross above the target area. It is possible that the two prospects can be tied, but we do not recommend a large expense to effect a tie.

The cost is estimated as $75K to $100K for the joint survey.

Recommendation: Low Priority Areas

Ranking of the remaining prospects is rather arbitrary, and will doubtless change with events of the next year or so, as study progresses under the DOE contracts. We recommend against spending anything on these areas at this time, even though we offer the following ranking:

Roosevelt, if GSI purchase fails--reshoot the GSI line or get some of the Phillips data

Colado--looks like another RFF, will contribute little provided Leach or Dixie Valley surveys are conducted

Roosevelt, with GSI data--additional lines(s)

Beowawe, Getty--wait for Chevron Beowawe data.

Long-Term Outlook: Interesting Prospects

Several prospects are interesting in the long term, and should be watched while developing. No expenditures are recommended at present for seismic data acquisition. These are Desert Peak, McCoy, and Tuscarora, each unique in some way.

IV. OBJECTIVES OF MARINA DEL REY CONFERENCE

In order to review the progress of the Geothermal Exploration and Assessment Technology Program and define the future objectives of that program, technical review committees were convened at Marina del Rey, California during May 14-16, 1979. The following is a memo outlining the objectives and the agenda of that meeting. To improve coordination among program, the technical advisory group of the Geothermal Reservoir Engineering Management Program (GREMP) was convened at the same time and place. Their report makes up section XI of this document.

INTRODUCTION

The U.S. Department of Energy, Division of Geothermal Energy (DOE/DGE) has an established program in Geothermal Exploration and Assessment Technology. The purpose of this program is to provide assistance to the Nation's industrial community by developing new technology of a geoscientific nature in geothermal exploration and reservoir assessment. Management assistance to DOE for this program is provided by the Earth Science Laboratory of the University of Utah Research Institute (ESL/UURI).

It is extremely important that the work done under this program be responsive to the needs of the industries which are engaged in development of geothermal energy. Therefore in the process of program planning it is imperative that guidance be actively sought and incorporated into the plan by DOE/DGE and by ESL/UURI. This conference has been convened for the purpose of providing such input.

DOE has also invited participation from members of the reservoir engineering community at this conference. The purpose is to provide input to DOE and to LBL regarding the DOE-funded reservoir engineering programs. Separate instructions regarding the desired output from the reservoir engineering working group meetings will be furnished by DOE and LBL.

At the conclusion of this conference, the chairmen of the several Technical Review Committees will each submit a written report of their Committee's activities, recommendations, and priorities. These reports will be collated into a conference report which will be distributed to all participants. In addition, the reports will be sent to other geothermal program managers from industry for their comments. The recommendations and priorities will be used by ESL/UURI in completing a revision and update of the Geothermal Exploration and Assessment Technology Program Plan for DOE. Justification, work plans, and budget for the program ultimately authorized by DOE will be based on this Plan.

AGENDA

The technical review committees will meet individually in working groups to each generate a report which focuses on the specific geoscientific problems facing industry in geothermal exploration and assessment. Generation of this report is the responsibility of each group's chairman and the report should be in final form for typing by noon, May 16.

It is anticipated that the committee working groups will spend the Monday sessions outlining their reports. During this time problems may arise which are outside the areas of expertise of the group members. If this happens appropriate members from other groups should be invited to take part in working group discussions on Tuesday morning. This must be done discriminately to avoid disruption and depletion of the lending group, and borrowing should not be done before Tuesday morning. Obviously, ample opportunity will exist for communication on an informal basis.

Two plenary sessions are scheduled. During these sessions each committee chairman will give a 15-20 minute summary of the progress his group has made in defining problems in need of DOE-funded research. Feedback of a critical but constructive nature is expected from the audience. If you feel that a group is off track or is not addressing subjects which will improve geothermal exploration and assessment cost-effectiveness and success, this will be the time to let your thoughts be known. In addition, this will provide the opportunity for discussion of the relative contributions to geothermal exploration and assessment from solution of the problems defined within each working group. It will also provide the opportunity to ask the critical question "why does your group believe that recommendation to be important? "

Attached to the back of this document is an agenda for the meeting. This agenda outlines a rather full schedule. Your support in providing your expertise during all of the meeting hours will be very much appreciated. An early afternoon termination of meetings on Tuesday (4:00 PM) is scheduled, and your duties will end (except for chairmen) by noon on Wednesday. We hope you will each find enough time during free hours to enjoy Marina del Rey.

TOPICS

The technical committee working groups should focus on present and future problems in geothermal exploration and assessment. Final committee reports from a similar conference held about one and one-half years ago (Ward, 1978) will be provided as a base to build upon. In addition, the progress made by DOE contractors on previous recommendations will be reported to you. The report of each committee should concentrate on present and future problems and the research needed to alleviate these problems.

The focus should be on the specific geoscientific problems facing industry. In this task our industry participants will play a key role. Practical, cost-effective solutions to these problems are required and will be the subject of DOE-funded research efforts. Problem definition should include subjects which are both site specific and regional in nature, even though primary resonsibility for research on regional problems rests with the U.S. Geological Survey. Problems which may require a long range research effort should be considered as well as those which can be solved in the short term. The exploration impact of each problem and the relative priority for DOE-funded technology research should both be discussed and addressed in the final report.

In addition to specific topics suggested for each working group (considered further below), it is requested that all of the groups cover the following topics and questions and respond in the report.

1. What should the objectives of the DOE/DGE Exploration and Assessment Technology and Reservoir Engineering Programs be in the near- and mid-term (i.e., the next 5 years); in the far-term? Suggest specific milestones for achieving these objectives.

2. What effect has the National Energy Act had on geothermal exploration in general, and what effect do you think that it will have on increasing the amount of geothermal power on line in the near-term?

3. Each group should prepare an outline scenario which gives their consensus on the best overall DOE program (including recommendations from the other working groups) at the $2.5 M and $5 M level in exploration and assessment technology. This can best be done in the second and third days when preliminary reports from other working groups will be in your hands. What is the necessary minimum DOE funding level for exploration and assessment technology to make a significant impact on exploration cost-effectiveness and resultant power on line?

4. It is probable that the Geothermal Exploration and Assessment Technology Program will initiate technology development efforts in the areas of low- to moderate-temperature geothermal resources in the near future. Some of the technologies used for exploration and assessment of high-temperature hydrothermal convective systems may not be directly applicable to moderate- and low-temperature systems, not only because of the different physical and chemical manifestations of the system, but also because exploration will often take place in populated areas and because the value of the resource will often not warrant expensive exploration techniques. You should add a component not considered during previous workshop efforts - geoscience technology development for low- and moderate-temperature resources.

5. Each group should consider and recommend specific rock properties measurements required for modeling geothermal systems. Also suggest how

to best obtain these property measurements (i.e., lab, in situ, well log interpretation).

6. Make specific recommendations for the most efficient means of transferring technology developments to industry. In-house reports are the most rapid means of disseminating information, but these reports fall into the realm of "gray literature", that is, they characteristically have a limited distribution and poor availability after initial publication.

COMMITTEES

Following are outlined the basic objectives of each committee. These lists are meant for discussion and each group has the prerogative of indicating that the defined objectives have missed the mark and, of course, indicating what the proper objectives are.

Structure, Stratigraphy & Igneous Processes

This committee is designed to provide a core of geologic input, and will to a large extent define problems which may be solved by programs in geology, geophysics and geochemistry. On the other hand, a group of problems exists which the geologist is uniquely qualified to solve. This committee is likely to consider most of the problems faced by project managers who are running geothermal exploration programs. Topics that might be discussed include.

1. Reservoirs are structurally or stratigraphically controlled and those of high temperature require an important active structural component to prevent self-sealing. In a high-temperature environment, the success of a well is dependent on intersecting a permeable fault or fracture.

Permeability commonly changes along strike. What can be done to increase our knowledge of fault systems, their geometries, their relative and space-varying permeability, and the importance of secondary structures?

2. Do you find existing geologic mapping adequate? Should DOE/DGE sponsor geologic mapping in areas of active geothermal exploration?

3. What are the conceptual differences between high- and low-temperature hydrothermal systems?

4. How can additional knowledge of the relationship between igneous activity and geothermal systems influence geothermal exploration?

5. What rock property measurements need to be made?

Seismic Methods

The objective of this committee is to review the present use of active and passive seismic surveys in geothermal environments and recommend additional work necessary to document and/or improve the usefulness of seismic techniques in geothermal exploration and assessment. You are provided with a seismic data base selected from data which has been placed in the public domain as a part of the Industry Coupled Program of DOE/DGE. In addition you are provided with the recommendations of Ron Ward, Tom McEvilley, and Stan Laster on the seismic portion of the Exploration and Assessment Technology Program for FY 79. Much of the problem definition concerning the utility of seismic methods in geothermal exploration was achieved at the APSMAGS workshop in Taos, New Mexico last fall. Your report should suggest and prioritize specific research projects to solve existing problems and controversies. You should indicate approximate costs to solve problems suggested. Some topics which may be addressed during your discussion are:

1. What research and technique development work is needed in data acquisition and interpretation in areas of high structural complexity, steep dips, and small velocity contrasts between major rock bodies, such as geothermal systems often represent?

2. What rock properties need to be better determined to enhance the utility of seismic techniques?

3. How can the costs of obtaining quality seismic data over geothermal areas be decreased so that they are more easily justifiable in the budget framework most companies have for geothermal exploration or reservoir assessment? Can a cost-effectiveness value be estimated for seismic information?

4. What work needs to be done to establish the utility of seismic noise surveys and microearthquake surveys to geothermal exploration and assessment?

5. How can fractures, particularly open fractures, be detected at depth up to 10,000 feet in geothermal areas with enough precision to allow intersection by drill holes?

6. Can recording out to long times, such as 30 seconds during vibroseis or dynamite source surveys, be used to determine the nature of the deep crust beneath geothermal systems?

7. What are the minimum acceptable sampling rates and group spacings for reflection seismic surveys in geothermal exploration?

Water/Rock Interaction

This committee has the broad task of recommending research into the use of chemical and mineralogical indicators present in geothermal systems, specifically as these indicators may be applied to geothermal exploration and assessment. This task spans a range of topics from chemical geothermometers and methods of determining fluid entries or approach to fluid entries during the drilling process, to determining district-wide zoning as an aid to drill site selection. You may wish to address the following topics:

1. How can fluid entries or the approach to fluid entries be predicted during the drilling process (trace elements, continuous monitoring of volatiles, isotopes, petrology)?

2. What improvements are needed in chemical geothermometry? Isotope geothermometers? Low-temperature geothermometers?

3. Numerous exploration companies have suggested that zones of overlapping hydrothermal alteration present interpretation problems. How can alteration zones of different age be most conveniently separated?

4. How can geochemical and mineralogical work aid in reservoir engineering and hydrologic studies?

5. What work needs to be done to improve applications of geochemistry and mineralogy to exploration and assessment of low- and moderate-temperature resources?

6. How can computer modeling of hydrothermal convection systems be applied to geothermal exploration?

TABLE IV.1

GEOTHERMAL INDUSTRY EXPLORATION STRATEGY AS INDICATED BY INDUSTRY COUPLED PROGRAM DATA PACKAGES

AREA	BALTAZOR	TUSCARORA	MC COY	LEACH H.S.	COLADO	BEOWAWE	BEOWAWE	SAN EMIDIO	SODA LAKE	STILLWATER	DIXIE VALLEY	DESERT PEAK	HUMBOLDT H.	COVE FORT-SULPHURDALE UTAH
COMPANY	EPP	AM	AM	AO	G	G	C	C	C	U	SR	P	P	U
DATA														
GRAVITY	E	X	X	E	E	X		E		E		E	E	E
GROUND MAG.					E	X						E		
AERO MAG.	E	X	X				E				E			E
ELEC. RES.					E	X	E	E	E	E				E
MAGNETO-TELLURIC		X	X	X	E		E		E	E	E	E	E	
AUDIO MAGNETO TELLURIC					E									
SELF POTENTIAL		X	X				E	E						
SEISMIC EMISSIONS							E	E						E
MICRO-EARTHQUAKE	E	X	X				E							
SEISMIC REFL. (weight drop)							E		E					E
SEISMIC REFL. (CDP 12 or 24 fold)			X	X			X	E	E					
GEOLOGY	E			E				E			E X	E	E	E
GEOCHEMISTRY	E			E							E			E
SHALLOW TEMPERATURE											X			
SHALLOW THERMAL GRADIENT	E	E X	E X	X	E X	X		E	E	E	E			E
DEEP THERMAL GRADIENT	X	X	X	X	X	X			E X		E X	E		E
EXPLORATION WELL	X	X	X	X	X	X	E	E	E	E	X	X	X	E X
FLOW TEST (if appropriate)	X	X	X	X	X	X	X			X	X	X	X	X

COMPANY EXPLANATION

EPP - Earth Power Production
AM - Amax Exploration Inc.
AO - Aminoil USA, Inc.
G - Getty Oil Co.
C - Chevron Resources Co.
U - Union Oil Co. of Ca.
SR - Southland Royalty Co.
P - Phillips Petroleum Co.

E = *EXISTING DATA*   X = *NEW PROGRAM*

7. Knowing regional geology, is it possible to predict units which have the highest potential for forming good reservoirs based on their chemical/mineralogical composition and resultant physical properties in both altered and unaltered state?

8. The geothermal industry routinely drills shallow to intermediate depth holes for the determination of thermal gradients. Suggest additional mineralogical, chemical, and hydrological data which should be routinely collected during this drilling. Is the present knowledge of regional zonation patterns sufficient to apply this data after it is collected? Is basic research into the mobility of trace elements with respect to temperature required?

Exploration Architecture

The purpose of the Exploration Architecture committee is to recommend integrated geological, geochemical, and geophysical approaches to improve the success and cost-effectiveness of geothermal exploration efforts. Table IV.1 showing the types of data being contributed to the Industry Coupled Program in northern Nevada. The variety of different methods being employed is impressive, but it suggests that there are many approaches to exploration rather than a carefully considered methodology. Conceptual models of geothermal resources are obviously important considerations in formulating an architecture. To be meaningful, an architecture must take into consideration the unique features that each geothermal prospect presents as well as the fundamental similarities.

Some of the topics which this working group may want to address are:

1. What type of project work should DOE fund so that improvements in exploration architecture can be realized?

2. In a usual exploration program, what are the questions which are usually most difficult to answer using the broad range of geological, geochemical and geophysical techniques available, i.e. what knowledge gaps are left after the presently available methods are used?

3. Of the presently available methods known to be effective, what cost-effective combinations and sequences of application exist for each of the important resource types?

4. Discuss cost-effectiveness of individual geoscientific methods.

5. Most exploration architecture schemes are predicated upon expected physical and chemical responses of the geologic environment. However, unexpected geologic conditions may require a modification of commonly used techniques or a substitution of other methods. For instance, electrical techniques are not effective for tracing faults beneath playas. What are the alternatives for mapping these buried fault zones? In general, what alternative exploration architectures exist when problems arise?

6. What are the specific differences between exploration architecture for high-temperature resources and for low- and moderate-temperature resources? Is work needed to develop effective exploration architectures for the low-temperature environment?

Electrical Methods

A great variety exists in available electrical methods and in their utility and cost-effectiveness. This generates differences of opinion among geophysicists regarding which electrical method to use for what purpose and in which situations. Potential topics for DOE-funded technology development span the range from better instrumentation to better field techniques and better interpretation. Some of the topics this working group should consider are:

1. What is the use and cost-effectiveness of each method?

2. On a method-by-method basis, what DOE efforts are needed to solve problems with instrumentation, field techniques and/or interpretation?

3. What rock properties studies are needed for the better use of electrical techniques?

4. Are there new electrical techniques which offer promise for cost-effective contribution to geothermal exploration and assessment?

5. What role, if any, should induced polarization surveys play?

Thermal Methods

Thermal methods have the advantage of directly detecting the commodity of interest to the geothermal industry, namely heat. However, many problems stand in the way of making effective use of thermal methods for remote detection of resources. Spurious effects due to ground water circulation and lack of adequate samples for good thermal conductivity determinations (to be used with good temperature gradient data) are two of these problems. Thermal methods can contribute both to the regional picture and to the site-specific picture. Some topics this working group may want to consider are:

1. Are equipment improvements needed?

2. What are the problems that need solving in data interpretation? How about complex models which include hydrologic data and models?

3. What rock properties measurements are needed?

4. How can data acquisition be improved, and what DOE-funded programs are needed?

5. What is the role of thermal methods in exploration and assessment of low- and moderate-temperature resources?

ET REQUIREMENTS DOCUMENT

The Resource Applications (RA) section of DOE/DGE (under the direction of Rudy Black) has been charged with establishing R&D requirements to support commercialization of geothermal energy. One component of this will be a document addressed to the Energy Technology (ET) section (which is headed by Benny DiBona). The person responsible for organizing and bringing together this ET Requirements Document is Joe Hanny of EG&G, Idaho. The present meeting is being used to provide outside input into the Requirements Document in the area of Reservoir Assessment (Robert Gray - Section Chief for ET). This includes programs dealing with Reservoir Evaluation, Exploration Technology, and Reservoir Engineering. Input is also requested for programs which address the Geoscience Programs of Hydrothermal Technology (Clifton McFarland - Section Chief for ET). These programs include Log Instrumentation, Well Log Interpretation, Subsidence, and Induced Seismicity. The meeting to provide this outside input is scheduled for 8:00 PM on Tuesday, May 15; all interested parties are invited to attend.

AGENDA

MONDAY, MAY 14	8:30-10:00 AM	INTRODUCTION Exploration & Assessment Technology Program - D.L. Nielson Reservoir Engineering Program - J.H. Howard Remarks - R. Gray M. Reed L.L. Mink
	10:00 AM-NOON	WORKING GROUPS Establish Objectives Outline Report
	NOON-2:00 PM	LUNCH Numerous restaurants in proximity of Marriott.
	2:00-4:00 PM	WORKING GROUPS Outline Report Writing Assignments
	4:00-6:30 PM	PLENARY SESSION Reports by group chairmen - audience feedback
	6:30 PM	NO HOST BAR BY POOL
TUESDAY, MAY 15	8:00 AM-NOON	WORKING GROUPS Writing reports Considering feedback from plenary session. Special Topics. Members of other groups may be invited to input. Consider $2.5M or $5M DOE Program.
	NOON-1:00 PM	CATERED LUNCH AT POOLSIDE
	1:00-4:00 PM	PLENARY SESSION Reports by group chairmen, audience feedback
	4:00 PM	UNSCHEDULED
	8:00 PM	Meeting to discuss ET Requirements Document J. Hanny, F. Simpson - EG&G, Idaho W.S. Bennett - LATA.
WEDNESDAY, MAY 16	8:00 AM-NOON	WORKING GROUPS Completion of individual committee reports.
	(1:00-1:30 PM	Report by Chairmen.)

V

FINAL REPORT

STRUCTURE, STRATIGRAPHY AND IGNEOUS PROCESSES

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Dennis S. McMurdie (Chairman)	Southland Royalty Company
William P. Nash	University of Utah
Dean Pilkington	Amax Exploration Inc.
John Sonderegger	Montana Bureau of Mines

STRUCTURE, STRATIGRAPHY AND IGNEOUS PROCESSES COMMITTEE

This committee has reviewed the basic objectives set forth in the outline for discussion. In our discussions we integrated the comments of industry, government regulatory groups and the academic community which deal with geothermal programs pertaining to Structure, Stratigraphy and Igneous Processes.

SURFACE GEOLOGY

Objective

Establish the geologic framework for areas with potential or established geothermal resources.

Justification

The geologic setting needs to be established to aid in the interpretation of structural, geophysical and geochemical studies of the area, as well as for ecological studies, well siting and subsurface control for proposed wells.

Recommendations

A. Detailed geologic mapping should be undertaken at potential or established geothermal resource areas. We recommend that this be at 7-1/2 minute quadrangle scale, or in greater detail in conjunction with low level and low sun angle aerial photography, or other forms of remote sensing when needed.

B. Geologic mapping should extend beyond the specific site to provide sufficient information on the surrounding regional structural and tectonic setting.

Cost: 3 maps/year @ $75K/map = $225K/year for 5 years.

SUBSURFACE STUDIES

Objective

To provide reasonable detailed information about the subsurface geologic framework of potential or known geothermal resource areas with particular emphasis on lithologic and structural relations.

Justification

Subsurface studies are needed to permit the extension of surface geologic and geochemical data into a three-dimensional framework. Commonly, secondary porosity and permeability can be related to the structural history deduced from these studies. This type of information is needed for preliminary inputs to evaluate reservoir characteristics and provide a base to monitor change with time during reservoir production (specifically gravity), should production occur.

In the eastern part of the U.S. where low temperature and geopressured resources are to be evaluated, the compilation of existing, available subsurface data should be considered the first step in resource evaluation.

Recommendations

A. Site-specific structural studies should be made at potential or established geothermal resource areas. The studies should be integrated with the regional tectonic framework, and may involve use of fission track and K-Ar age dating to establish rates of tectonism and sequences of structural events.

B. Detailed gravity studies should be undertaken early in the exploration of geothermal resource areas.

In established geothermal fields, gravity studies should be continued to monitor the system and assist in defining the configuration of the reservoir as well as recharge.

Cost: A. $40K/yr

B. Gravity. 3 surveys per year @ $35K per survey = $105K per year for 5 years.

ROCK PROPERTIES

Objectives

To obtain data on the properties of the subsurface that can be utilized to enhance exploration and exploitation of the geothermal reservoir.

Justification

The parameters to be measured can be used to define the limits of the reservoir boundary. They can be used as well to define the production and porosity zonation as well as the recharge and source areas.

Recommendations

A. Measure the following rock properties in established geothermal areas:

a) *in situ* stress

b) rock density

c) Poisson's ratio

d) magnetic susceptibility

e) resistivity

f) fracture density and/or permeability

B. Support studies described by the rock-water interaction committee including mineralogical alteration, water chemistry, and carbon, hydrogen, oxygen and sulfur isotopic studies.

Cost: A. 1 site. 3 to 5 wells per year: $30K

IGNEOUS PROCESSES

Objective

A. Establish in greater detail the ages of igneous activity in areas with potential or established geothermal resources.

B. To establish a more comprehensive understanding of the relationship between magmatic activity and geothermal resources, and develop new techniques to assist in exploration for geothermal resources.

Justification

A. Age relationships of igneous activity are vital to the exploration for geothermal resources, and the current data base is inadequate.

B. As readily identifiable resource areas become scarce, it is important to develop a more sophisticated understanding of how magma bodies are generated and emplaced, and ultimately cool in the upper crust.

Recommendations

A. Continue to support age dating of igneous rocks, preferably at an accelerated rate.

B. We recommend that each state participating in the State Coupled Program compile a catalog of K-Ar dates that have been obtained in samples from the state.

C. Develop models for the evolution of magma systems in the manner applied to porphyry copper systems. These should examine problems of magma genesis, magma transfer in the crust and cooling of magmas, and the thermal decay of hot solid igneous bodies. The latter aspect will involve water-rock interaction and alteration studies.

D. The chemical compositions of silicic igneous rocks may be related to the magnitude of the magmatic system. Detailed chemical studies should be undertaken to evaluate this potential exploration technique.

Cost: A. $75K/yr for 5 years

B. To be funded to State Coupled Program

C. $40K per year for 3 to 5 years

D. $40K per year for three to five years

COMPARISON OF HIGH VERSUS LOW TEMPERATURE HYDROTHERMAL SYSTEMS

While magmatic heat sources may produce either a high- or low-temperature resource, low-temperature resources may be characterized by a wider range of geologic environments. In low-temperature systems: 1) the heat source may be solely from the regional geothermal gradient (including radioactive decay) and deep circulation; 2) higher permeabilities and thermal conductivities may be present in the source and transmission zones; 3) capping units may not be present; 4) target reservoirs may lie above the main reservoir/source zone;

and 5) because some of these targets will be shallow, the risk of degradation of the resource is higher by inducing recharge of colder native ground water into the reservoir.

Use of standard approaches combined with procedures developed for groundwater studies are deemed adequate for most purposes.

PRIORITIES, IN ORDER OF IMPORTANCE

1. Surface geology
2. Potassium-argon age dating
3. Subsurface studies
4. Rock properties
5. Other igneous studies

VI

FINAL REPORT

EXPLORATION ARCHITECTURE

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Robert McEuen (Chairman)	Exploration Geothermics
Norman Goldstein	Lawrence Berkeley Laboratory
Bill Isherwood	USGS, Menlo Park
George Jiracek	University of New Mexico
Dick Lenzer	Phillips Petroleum
Tsvi Meidav	Consultant

EXPLORATION ARCHITECTURE

The goal of geothermal exploration architecture is the integration of geological, geochemical, and geophysical approaches in such a way as to improve the cost-effectiveness and success of exploration efforts. Clearly no one architecture can meet the needs of the industry. However, general statements can be formulated regarding the present effectiveness of the available techniques in finding various kinds of geothermal resource targets in various kinds of geologic provinces, and regarding those techniques which might show significant improvement if additional research were conducted.

METHOD USED TO IDENTIFY ARCHITECTURE COMPONENTS IN NEED OF DOE SUPPORT

Each component that may contribute to an exploration program in four differing geologic provinces was evaluated for its applicability to the resource search and for its relative need of additional support. Each component was graded as to its ability to locate seven differing resource types and the need for support to improve its effectiveness was determined. Each component was evaluated in terms of its ability to withstand "noise" both natural and man-made, and a judgement made whether this ability could be markedly enhanced through additional funding.

The relative ease of collection of the data necessary to use each component was determined and the extent to which additional funding could be expected to improve this condition rated. All the above considerations were assessed for both "regional" and "site specific" components.

Two members of the committee had been party to a similar ranking exercise carried out by the Mitre Corporation in November of 1978. The Mitre survey had a total participation of thirty-five respondents. A comparison was made between component effectiveness as determined by the larger Mitre sampling and that determined by the committee. No ranking with respect to need for additional government funding is contained in the Mitre report.

After identifying components that could potentially profit substantially from additional funding, the Committee discussed these components with the Technical Review Committees charged with the function of recommending research in specific areas. If applicability and need were clearly established, the component in question was further discussed and a level of appropriate support determined.

ARCHITECTURE COMPONENTS RECOMMENDED FOR FUNDING

Components with Applicability as Identified by the Committee and by the Mitre Report

The process described in the above section led to the isolation of the following components as being worthy of additional support. The applicability of these components within the geotechnical constraints indicated was previously recognized by the group polled by the Mitre Corporation. These specific components include:

1) Refinement of the magnetotelluric method to delineate high-temperature resources in areas such as the Basin and Range and the Rio Grande Rift

   250K/yr.

2) Effect of ground water flow on thermal and gradient measurements in problem areas

   100K/yr.

3) Regional application of liquid geochemistry to areas where the fluids are expected to be of low salinity and moderate temperature

100K/yr.

4) Regional application of gas geochemistry in areas of expected blind resources

100K/yr.

5) Use of age dating in problem areas such as the Cascades

100K/yr.

6) Use of joint collection and inversion of data to effect economy of field operation and to reduce ambiguity in interpretation

50K/yr.

Recommendations from Other Review Committees for Research Directly Related to Exploration Architecture

The Committee would like to go on record as supporting the following recommendations of the other Review Committees:

1) Regional contour map of the "Deep Electrical Conductor."

2) Compilation of all existing regional seismic data.

3) Applied research in processing DOE-acquired reflection data.

4) DOE-USGS Refraction - Deep reflection survey at the Clear Lake Volcanic Field.

5) Study of the use of I.P. methods in known geothermal regions.

6) Evaluation of the magnetometric method for location of deep elongated conductors.

7) Up-dating and refinement of available regional temperature maps.

REVIEW OF MITRE REPORT

The MITRE report (Dhillon et al., 1978) was aimed at assessing the benefit/cost ratio that may result to the economy if certain incremental improvements in drilling success ratios are to be achieved. Based upon analysis of the current success ratio, and the ultimate goal of 20,000-30,000 megawatts on-line by the turn of the century, it was estimated that a sum between $220 million and 2 billion dollars will be saved to the economy by increasing the overall success ratio by a few percentage points. Accordingly, the MITRE report recommended that a sum of about 22 million dollars (10% of the most conservative savings to be achieved) could be spent immediately on exploration technology improvement.

As part of the study, MITRE canvassed 35 individuals and companies engaged in geothermal exploration to obtain their opinion about the regional applicability of various exploration or assessment techniques (Table VI.1). The most applicable method was ranked as number 1, and the least applicable method was ranked as number 14, for all 14 techniques which were listed. Table VI.1 does not concern itself with cost-effectiveness, but rather with the degree of applicability of the method as an independent method, in either locating the target or assisting in defining some of its components.

Based upon inspection of Table VI.1, it is possible to construct distinct exploration architectures in a number of different geological provinces as shown in Table VI.2. The ensembles of techniques shown in Table VI.2 were implicitly judged by the respondents as the most suitable for each region.

TABLE VI.1

EVALUATION OF REGIONAL APPLICABILITY OF EXPLORATION/ASSESSMENT TECHNIQUE

TECHNIQUE	OVERALL REGIONAL RANKING APPLICABILITY	RANKING OF TECHNIQUES ACCORDING TO APPLICABILITY IN											
		SALTON TROUGH	BASIN AND RANGE	CASCADES	BASALTIC ISLAND REGIME	SNAKE RIVER PLAIN	WASATCH FRONT	RIO GRANDE RIFT	GEYSERS	ALEUTIAN ARC ISLAND	APPALACHIAN	EASTERN AND SE PLUTONS	GEOPRESSURED REGION
Thermal Methods	1	1	1	1	2	1	1	1	1	1	1	1	2
Surface Geological Mapping	2	9	2	2	1	2	2	2	2	2	3	5	9
Gravimetry	3	2	7	5	4	3	7	7	3	4	2	2	5
Electrical Methods	4	3	4	3	3	8	4	3	8	5	8	6	7
Borehole Logging	5	5	8	10	10	4	8	9	7	3	15	4	1
Seismic Methods	6	4	5	8	6	6	5	5	6	6	9	7	3
Liquid Geochemistry	7	6	3	4	5	9	3	4	5	7	6	8	4
Air Photogeology	8	7	6	7	8	5	9	8	4	9	7	9	12
Age Dating	9	10	9	6	7	7	6	6	9	8	10	10	14
Magnetics	10	8	10	9	9	10	10	10	10	11	4	3	6
Gas Geochemistry	11	11	13	13	11	13	13	13	11	12	11	12	8
Remote Sensing	12	12	12	12	13	11	11	11	12	13	12	11	10
Thermal Infra Red	13	13	11	11	12	12	12	12	13	10	13	13	11
Other	14	14	14	14	14	14	14	14	14	14	14	14	13

LEGEND

1 = Most Applicable to 14 = Least Applicable

Dhillon et al.,1978

The effectiveness of each of the currently employed exploration techniques was determined by its weighted average of respondent ratings on diagnostic capability, applicability, dependability and immunity to noise (background or geological), as shown in Table VI.3.

EXPLORATION ARCHITECTURE AS PRESENTLY PRACTICED

The geothermal industry is still very much in its infancy and undergoing what might be considered growing pains. Much research in exploration methods is still going on. Possibly the best indication of the cost-effectiveness of an exploration method is the frequency of use of the method by industry. The data submitted by industry as part of the northern Nevada Industry Coupled Program is an indication of the types of surveys that are routinely run in evaluating a prospect (Table IV.1). Admittedly this list is not complete as some surveys on the list are experimental and some surveys were not turned over to DOE because of their sensitivity.

What is very clear is that the methods are most frequently combined. The combinations typically include both shallow and deep thermal gradients, an electrical resistivity survey, gravity, and magnetics. The extent to which geologic and geochemical surveys are routinely conducted is not known but both should probably be included in the above group. The thermal methods are the most commonly used of all the techniques. It appears that industry considers that combining exploration surveys is effective in reducing the risks associated with deep drilling.

In order to decrease the costs associated with acquiring active seismic

TABLE VI.2

EFFECTIVE ENSEMBLES OF EXPLORATION TECHNIQUES IN VARIOUS GEOLOGIC ENVIRONMENTS

GEOLOGICAL ENVIRONMENT	USERS PERCEIVED MOST APPLICABLE TECHNOLOGY
Geysers	Thermal Methods Surface Mapping Gravimetry Air Photography Geochemistry
Salton Trough	Thermal Methods Gravimetry Electrical Methods Seismic Methods Borehole Logging
Basaltic Island Arc	Surface Mapping Thermal Methods Electrical Methods Gravimetry Geochemistry
Geopressured Zone	Borehole Logging Thermal Methods Seismic Methods Geochemistry Gravimetry
Basin and Range Snake River Plain Wasatch Front Rio Grande Rift	Thermal Methods Surface Mapping Geochemistry Electrical Methods
Appalachian Provence Eastern and S.E. Plutons	Thermal Methods Gravimetry Magnetic Methods
Cascade and Aleutian Arc Islands	Thermal Methods Surface Mapping Gravimetry Electrical Methods

Dhillon et al., 1978

TABLE VI.3

RANKING OF EFFECTIVENESS OF TECHNIQUES

TECHNIQUE	OVERALL RANKING	RANKING BASED ON			
		DIAGNOSTIC CAPABILITY	APPLICA-BILITY	DEPENDA-BILITY	IMMUNITY TO BACKGROUND NOISE
Thermal Methods	1	1	1	1	5
Liquid Geochemistry	2	3	4	2	6
Surface Geological Mapping	3	2	5	4	10
Electrical Methods	4	4	3	3	5
Seismic Methods	5	5	2	5	1
Gravimetry	6	7	6	7	3
Borehole Logging	7	6	8	8	4
Air Photogeology	8	8	7	6	9
Magnetics	9	9	9	9	8
Age Dating	10	10	10	10	7
Remote Sensing	11	11	13	13	12
Gas Geochemistry	12	12	12	12	11
Thermal Infra-Red	13	13	11	11	13
Other	14	14	14	14	14

Dhillon et al., 1978

data, we recommend that "group shoots" or "spec. surveys" be considered in areas that will be offered on a competitive bid basis.

DIFFERENCE BETWEEN EXPLORATION ARCHITECTURE FOR HIGH TEMPERATURE VS. LOW- AND MODERATE-TEMPERATURE RESOURCES

The question is inseparable from the difference between exploration based on the economics of electric power generation versus a direct heat application. That is, the major change in exploration strategy is dictated by economics. The typical direct-heat application is a low-budget operation that simply cannot afford expensive exploration methods. Development wells will generally be less than 500 m deep, hence the saving attained by better surface exploration programs is less.

The low budget exploration program for low- and moderate-temperature resources will be highly dependent upon public information. Consequently, it is important to these relatively small users to have certain regional data bases available to them. The following regional maps may have particular use: contour of the Curie isotherm, contour to top of "low electrical resistivity" layer, crustal thickness, Pn velocity, regional gravity, heat flow and thermal data (both measured and derived from geochemistry), and detailed geology in human resource areas. These are not truly research topics, but we do recommend a continued, moderate effort to generate and disseminate such maps.

Low-budget exploration will rely heavily on the relatively inexpensive techniques of geochemistry. Retrospective case studies of standard geothermometry techniques would enhance the prediction of shallow reservoir temperature. More research, demonstration and dissemination of results could similarly enhance the usefulness of gas and rock geochemistry.

Since both holes of opportunity and shallow thermal measurements are critical, we recommend a clear documentation of the geologic situation in which shallow thermometric heat flow data can be considered reliable.

Tools such as AMT which are not routinely used due to shallow penetration and lack of available equipment become very useful for shallow reservoir delineation. Equipment development and case history documentation is recommended.

Standard geologic and structural mapping techniques continue to be cost-effective but seem to require little new research support.

VII

FINAL REPORT

ELECTRICAL METHODS

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of the Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Frank Frischknecht (Chairman)	U.S. Geological Survey
Mark Ander	Los Alamos Scientific Lab.
John Maas	Phillips Petroleum Company
William Sill	University of Utah
W. Dal Stanley	U.S. Geological Survey
Charles Stoyer	Colorado School of Mines
Alan Ramo	Sunoco Energy Development Co.
Darrel Word	Geotronics

INTRODUCTION

In preparing this report we have reviewed the report of the 1977/78 consortium on electrical methods. We have also considered all of the topics suggested for our working group. We found many of the assumptions and recommendations made by the 1977/78 consortium to still be valid. However, there have been significant developments in the last 16 months which caused us to delete or modify some of the previous recommendations and to add new recommendations. In formulating our recommendations we have made the following assumptions:

1. Electrical methods are essential for geothermal exploration and assessment. Although not necessarily diagnostic, knowledge of the subsurface resistivity structure provides more information on the possible existence of a geothermal reservoir than any other surface geophysical information (with the exception of thermal data which must be acquired from drill holes).

2. As a generalization, electrical methods are not as well developed as other methods such as seismic. Consequently, electrical methods are not utilized as fully as they should be. Also, when dealing with complicated structures, such as is usually the case in geothermal areas, we are not able to extract all of the information inherent in the data due to lack of adequate modeling and interpretational techniques. An additional concern is the fact that the exploration staffs of many of the geothermal companies and of electrical contractors are not large enough or sufficiently well trained to do high quality or even adequate interpretation of electrical data.

3. More effort needs to be made in integration and interpretation of all geophysical, geological, geochemical and hydraulic information for specific areas. Existing geologic models of geothermal systems are inadequate for proper interpretation of geophysical data.

4. From industry's viewpoint the principal needs are:

   a. Contractors who collect high quality data using well-calibrated equipment.

   b. The ability to do inhouse or to contract for high quality interpretation of the data.

   c. Case histories and comparative data for systems which have good drill hole and other control.

   d. Regional electrical data bases.

   e. More systematic and complete transfer of technology and information.

5. Appropriate policy objectives for DGE in the electrical methods program include:

   a. Improve the state-of-the-art in electrical methods (hardware, data processing, interpretation).

   b. Disseminate case histories and theoretical and field studies of electrical methods over geothermal systems which have been extensively studied and which are relatively well understood.

   c. Establish regional electrical data bases including a map of the "deep electrical conductor" seen by MT measurements.

   d. Develop electrical methods for monitoring changes in producing reservoirs.

DISCUSSION OF SPECIFIC QUESTIONS ON ELECTRICAL METHODS

The group was asked to consider five questions dealing specifically with electrical methods.

1. "What is the use and cost-effectiveness of each method?" Any answers which could be provided to this question in 2 1/2 days would be highly subjective and would probably change if the same question was asked to the same group in a few months. No attempt was made to answer this question.

2. "On a method-by-method basis, what DOE efforts are needed to solve problems with instrumentation, field techniques and/or interpretation?" The following brief comments which overlap with some of the recommendations are offered.

   DC resistivity methods - no special effort needed although there was some minority opinion that further work and demonstration of bipole-dipole techniques is needed.

   MT - emphasize 3-D modeling and 2 and 3-D inversion and interpretation.

   AMT - instruments are needed but they will probably be developed without DOE help. Same need for interpretation as for MT.

   Magnetometer Array - No emphasis needed.

   Telluric - No emphasis needed.

   Controlled Source EM - Greatest emphasis should be placed on field studies, case histories, modeling and interpretation. Some work on reduction of noise from geomagnetic variations is needed.

   Self-potential - No special emphasis needed.

"What rock properties are needed for better use of electrical techniques?" - Resistivity measurements at moderate temperatures and pressures characteristic of hydrothermal systems and measurements at higher temperatures up to melting.

4. "Are there new electrical techniques which offer promise for cost-effective contribution to geothermal exploration and assessment?" The use of magnetometric resistivity, large array MT, and short offset and coincident loop time domain EM methods should be considered.

5. "What role, if any, should induced polarization play?" Additional tests of IP techniques to identify clay-bearing and other hydrothermally altered rocks should be considered.

DISCUSSION OF GENERAL TOPICS

The group considered six general questions which were asked of all groups; brief answers are as follows:

1. DOE/DGE objectives:
   The primary objective of the DOE/DGE Exploration and Assessment Technology and Reservoir Engineering Program should be to 1) provide basic data such as regional geophysical data which industry will not acquire by itself and 2) to develop, improve, and demonstrate advanced and effective techniques for exploration and assessment which, for various reasons, will not be developed by industry. More detailed specific recommendations for electrical methods are given later in this report.

2. National Energy Act:

Members of the Electrical Consortium did not have sufficient information to comment on the effect of the National Energy Act.

3. Overall DOE Program:

The Electrical Consortium strongly believes that electrical methods must be a major part of the program.

4. Low-temperature resource assessment:

It is assumed that the availability of geothermal resources is such that there are minor amounts of dry steam resources, a significant number of isolated high temperature, hot-water systems, and broad areas of low-to moderate-temperature hydrothermal resources. It is believed from present data that lower temperature hydrothermal systems are anomalous electrically in much the same manner as high temperature systems, partially because the effect of temperature differential from 150°C to 250°C is not very significant but not dominantly because alteration products are most usually directly responsible for the thermally associated anomaly. Thus, no new prospecting techniques are needed specifically for low-temperature resources. However, a regional map of deep electrical properties would be important to prospecting for low-temperature resources and a specific proposal for a map of the "deep MT conductor", which would partially meet this need, has been outlined elsewhere in the electrical methods consortium report.

5. Rock properties measurements:

Rock properties studies are fundamental to many of the geophysical methods; therefore any physical properties measurements suggested should be coordinated with the requirements of other groups. Certain of the properties (density, porosity, etc.) as well as the controlled parameters (temperature, pressure, etc.) are common requirements. Effectiveness of the program would be improved by making as many measurements as feasible on the same rock samples. Specific details on the electrical rock properties requirements are discussed in the recommendations.

6. Dissemination of government geothermal research reports:

   All committee members seemed to agree that some systematic method of disseminating the results of government-sponsored research should exist. It was agreed that the current system of each research agency sending reports only to those consumers who from happenstance appear on their mailing lists is highly wasteful of federal money. Research results often do not reach the industrial consumers they are ultimately intended to aid.

   Three proposals were advanced to remedy this situation:

   a. A geothermal information center should be established where all this literature is deposited and with a library-type catalog so subjects, authors, and titles can be readily referenced. Possibly one or more such centers might be operated under contract by major university libraries.

   b. A geothermal bibliography might be published. A loose-leaf or card format could be followed so individual users who subscribe to the service could maintain a constantly updated, complete bibliography of all federal geothermal research. Entries for new work would be sent out as available.

c. In addition to the other approaches, it may be desirable to establish a master mailing list of major geothermal operators which would be supplied to all federal research agencies and grantees. Copies of reports would be automatically sent to all parties on that list.

RECOMMENDATIONS FOR SPECIFIC RESEARCH

The Electrical Methods Consortium recommends that DOE continue to support ongoing work in at least three areas and that they support three other new projects.

Ongoing projects which must be continued - listed in order of priority:

1. EM modeling and inversion;
2. Controlled-source EM field studies;
3. Rock properties measurements.

New projects which should be funded - listed in order of priority:

1. Preparation of regional map from MT data;
2. Establishment of calibration sites and procedures;
3. MT workshop.

EM Modeling and Inversion

One of the barriers to more efficient use of the electrical methods (especially EM/MT) is still the lack of accurate and cost-effective 3D modeling programs. One-dimensional modeling and inversion, because it is relatively easily and cheaply implemented, is often applied to EM/MT data. In this context, 3D model studies are important even if they are relatively expensive, since they can point out the instances in which 1D and 2D modeling or inversion can lead to misleading interpretations. Some of the recent work in 3D modeling has helped in this type of analysis. Further work is still required to improve the accuracy, reliability and cost-effectiveness of 3D modeling programs if they are to become efficient methods for the interpretation of electrical data from complex environments.

Inversions in terms of simple 2D models, and perhaps in terms of simple 3D models, might be carried out through interpolation of curve catalogs. However, it might be significantly more useful to invert these data in terms of anomalous currents. This is because the data do not contain the information necessary to define the subsurface electrical structure in the first place. Still, in this case, 2D and 3D modeling programs are required as a means of testing and calibrating these inversion methods.

This is one alternative; others might be directed at new methods of displaying and processing data to make them more transparent. Such a process would produce something between a pseudosection and an inverse model solution. It would not define the earth's resistivity structure, but, unlike a pseudosection, it would not be misleading.

The following are recommended:

a. Continue the development of cost-effective 2D and 3D modeling programs with emphasis on improvement and implementation of existing software. 300K/year - 3 years.

b. Develop alternate inversion schemes such as inversion to scattering currents. 100K/year - 3 years.

Controlled-Source EM Field Measurements

For many purposes controlled-source EM methods potentially offer greater resolution and other advantages over other electrical techniques. There are a number of important exploration problems which will probably be solved only by controlled-source EM measurements. A few controlled-source EM systems which are capable of measurements to considerable depths have been developed or are under development. Some additional work is needed to develop better instrumental or processing techniques for discriminating against geomagnetic noise. However, of greater importance is the collection and dissemination of controlled-source measurements for a variety of areas. More field data are badly needed to help establish the effectiveness of controlled-source methods and to guide the development of better methods for interpretation. We recommend that controlled-source EM field studies by at least two groups be carried out at Roosevelt Hot Springs, some of the industry coupled sites in northern Nevada, and perhaps elsewhere. The recommended level of funding is 100K/year for two years to carry out studies at approximately eight sites.

Rock Properties Measurements

The first goal of the interpretation of electrical measurements is to describe the geometrical distribution of electrical parameters in the subsurface (the geoelectric structure). Another goal should be to interpret this geoelectrical structure in terms of the geology and to relate the electrical parameters to other physical parameters that may be of more direct importance.

Knowledge of the dependence of the electrical properties on other physical properties (porosity, permeability, mineralogy, etc.) and parameters (salinity, temperature, etc.) provide a basis for this further interpretation. Laboratory measurements of the simulated *in situ* conditions can provide a data base for the development of empirical relationships and/or models that provide information on other physical properties or parameters.

The group feels that measurements are needed under conditions that simulate two probably quite different environments. One concerns moderate temperatures and pressures and relates to the conditions near or in the producing regions of possible geothermal reservoirs where conduction is predominantly by ionic and surface conduction mechanisms. The second is more concerned with the properties of the deeper crust, especially the conditions that produce the so-called "deep conductor" (5-30 km) that seems to be closer to the surface in some geothermal areas. The physical properties of this region and the conditions that cause an apparent rise in certain areas may have fundamental implications for the understanding of geothermal areas.

Most members of the group are impressed by the lack of relevant physical properties measurements despite previous strong recommendations. Some members of the group also believe that a modest systematic effort is needed to translate and disseminate foreign results, principally Soviet. We recommend funding rock property studies at 200K per year for three years.

Regional Electrical Map

It is recommended that DOE and USGS sponsor an effort to create a contour map of the depth to the extensive electrical conductor observed on many MT soundings at depths of 5 to 70 km in much of the western U.S. Such a map should be of great value in assessing the geothermal potential of large regions when utilized in conjunction with other data maps such as those compiled from heat flow, Curie isotherm, and P_n velocity.

We propose that a committee be formed to perform the following tasks:

1. determine the format of the map;
2. set specifications for an RFP which will be necessary to obtain proposals for reassessment of existing data by holders of the data;
3. decide the mechanism for producing the map when the MT data is obtained, possibly through an additional RFP.

None of the raw data for the map will be published, nor will detailed site locations be shown, in order to assure cooperation by holders of priority data.

Makeup of the committee should be MT specialists and MT users from industry, government, universities, national labs and MT contractors. The committee should provide the specifications to allow the Government to issue an RFP to obtain MT data sets which have to be reevaluated in light of the ceep conductor. We recommend funding of 50K per year for two years.

Recommendations on Standards for Calibration and Testing of Systems for Electrical Methods

Standard calibration schemes are needed for the deterministic testing of electrical data acquisition and reduction systems. Such schemes would provide the means for reliable assessment of entire system performance, including the instrumentation and any subsequent data reduction employed. Standard specifications would enhance uniformity of knowledge and application in the industry.

The committee recommends establishment of standards for calibration by two means: A) synthetic data tests and B) standard field test sites. Use of both schemes is recommended as the synthetic data test provides an accurate test of the system without uncertainties introduced by the noise and conditions of field environment, and the standard test site allows evaluation of performance with actual sensor installation and under field conditions.

A) Synthetic data test

Synthetic data test schemes are required for two basic types of methods:

a) The natural source system calibrator consists of a signal generator driving a network which produces electric (E) and/or magnetic (H) field signals of known characteristics as required by the method. A sample MT system calibrator consists of resistive attenuators to produce the E-field signals and a long current helix (or alternately a Helmholtz coil arrangement) to produce the H-field signals. E and H component groups, say (Ex, Hy) and (Ey, Hx, Hz), can each be driven by independent random noise generators. The effective MT impedance is determined by the source network parameters.

b) The controlled source system calibrator consists of a passive network which accepts the controlled source output and produces signals with known transfer characteristics to drive the receiving instrument(s).

For some systems a portion of the system might need to be deleted from the synthetic data test, for example, a large loop antenna for a magnetic source. For such a case, the missing portion of the system would need to be represented in the calibration network or accounted for in the expected response. Field calibration on an actual site of known characteristics should finally be performed to test integrity of actual sensor installation and overall field techniques.

Geotronics Corporation has already devised and implemented an MT synthetic data calibration scheme, and it was therefore recommended by the Electrical Methods committee that Darrell Word publish in Geophysics a short note documenting the scheme in order to make the information available in the literature.

B) Standard field test sites

Standard calibration and test sites for electrical methods equipment would:

1) Allow existing field equipment to be calibrated over known resistivities to ensure that accurate data is being obtained under field conditions.

2) Provide well-documented test sites for newly developed equipment and modifications of existing equipment.

There was general agreement that the following conditions should be satisfied in establishing the standard sites:

1. For convenience of access there should be several sites in different geographic areas.
2. There should be both "difficult" sites with complex subsurface geometry and "easy" sites which should approximate simple half-space or horizontally layered conditions.

3. The sites should be as well documented as possible; areas with good control over subsurface geometry and resistivity from deep well logs should be sought. This will be especially valuable in evaluating the performance of newly designed equipment. It may also be desirable to conduct electrical surveys of lands immediately adjacent to the calibration sites to determine what interference with calibration might be expected due to nearby bodies with contrasting conductivities.
4. Standard electrode positions should be clearly and permanently marked for equipment calibration use in order to achieve reproducible results. Such permanently marked electrode positions might, for example, be provided for X-spread MT and dipole-dipole soundings while leaving the experimenter with new equipment free to choose his own configuration.

To implement and make available a useable set of calibration standards for the electrical methods, the consortium recommends funding of a small program to produce a concise set of specifications of standards for both synthetic data testing and field site testing and to produce a single document of the specifications. The program should include a definition of the synthetic data schemes and the selection and description of field test sites and test procedures. The synthetic data calibration systems should be as basic and straightforward as is feasible for ease of reproduction. The field test sites should be selected in each of several locations on the basis of access convenience as well as various technical considerations.

Some work to this end has already been done by various groups and individuals; e.g., some test sites have been established and used, and some effective schemes for synthetic data calibrations are in use. The existing work needs to be extended and systematized toward production of the standard specifications.

It is recommended that an ad hoc committee be appointed to define an RFP on the overall project, to be let by DOE. The RFP should allow for sub-contracting of portions of the work, such as evaluation of proposed test sites, outside consulting on the calibration systems, and appropriate physical marking of the test sites. We recommend funding of 60K for one year.

MT Workshop

There has been considerable discussion of a workshop on MT methods and a specific recommendation was made by the 1978 consortia for such a workshop. The MT method is used extensively in geothermal exploration and regional assessment. A great deal of progress has been made in instrumentation and data processing in the past few years. At the present time the ability to produce high quality data has surpassed the ability to interpret such data; this is particularly true in the geothermal environment where two- and three-dimension structures seem to be the rule rather than the exception. A three or four day workshop for experts working in the field would serve to disseminate the results of recent efforts in instrumentation and processing as well as to serve as a forum to discuss interpretational problems. The USGS or DOE should fund such a workshop; the probable cost is 10-20K.

Additional Recommendations

In addition to the six specific recommendations for work to be supported by the DOE (or USGS), the Electrical Methods Consortium recommended that special attention should be given to the development and testing of several promising techniques which have not been used at all or have not been adequately tested in geothermal exploration. Some of this work might be carried out by university groups who have some flexibility in their use of DOE funding. The methods are--not listed in order of priority:

a. Induced Polarization

b. Magnetometric Resistivity

c. Long array MT measurements

d. Single or coincident loop TDEM method.

a. Induced polarization

Ideally, induced polarization methods could be used to help distinguish between low resistivity units which are due to the presence of clays from those which are due to hot saline fluids in porous media. In practice such discrimination is very difficult due to EM coupling, superimposition of effects, the tendency for membrane polarization to be a high frequency phenomenon, and other problems. Nevertheless, a modest effort should be made to study the use of I.P. methods in known geothermal regions where clay or pyritic alteration is known to be present.

b. Magnetometric resistivity method

The magnetometric resistivity (MMP) method has been shown to be very sensitive in the location of deep elongated conductors which serve as "channels" for current. By placing electrodes in drill holes which intersect permeable zones, it might be possible to trace such zones away from the drill holes by means of surface magnetic measurements.

c. Long array measurements

An interesting possibility is use of techniques which would tend to average electrical resistivity over large areas. In the MT method this could be done by using very long electric field lines.

d. Coincident loop method

A single or coincident loop time domain method is now being used fairly extensively in mineral exploration in the U.S.S.R. and in Australia. Large-scale measurements could be made in geothermal areas using equipment which mostly exists. Some of the potential advantages of this technique include discrimination against near-surface geologic noise and discrimination against lateral changes in resistivity; a loop one or two kilometers in diameter would be adequate for exploration to depths of a few kilometers.

VIII

FINAL REPORT

SEISMIC METHODS

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Ronald W. Ward (Chairman)	University of Texas at Dallas
David Butler	Micro Geophysics Inc.
H. M. Iyer	U. S. Geological Survey
Stanley Laster	University of Tulsa
Allan Lattanner	Union Oil Company
Ernest Majer	University of California, Berkeley
John Maas	Phillips Petroleum

INTRODUCTION

In this report the status of the previous and current DOE seismic projects will be summarized and a research and development program will be recommended. In addition, the committee feels several recommendations on the compilation and dissemination of data and information to the users is warranted. Also, recommendations will be made for future long-term research which, though not strictly relevant to immediate reservoir evaluation, will, in the long run, improve our ability in understanding and exploiting geothermal systems.

Previous and present developments in seismic techniques applied to Regional Exploration and Reservoir Assessment of a Prospect will be discussed and the background reasoning for the final recommendations will be treated.

Prior to making specific recommendations on tasks for DOE support, we briefly review how seismic information is critical to assess geothermal systems. Seismic surveys can aid in resolving the structural setting, determining the regional depth to the water table, identifying stratigraphy, and detailing fracture patterns. Other objectives are to obtain indirect evidence on the thermal regime, existence and state of fluid, porosity, and permeability of fracture zones. Microearthquakes have proved invaluable in mapping active faults which provide the conduits for water circulation and the existing stress field from fault-plane solution, stress drop, and energy release. The maximum hypocentral depths of microearthquakes are also useful in estimating the thermal regime surrounding geothermal reservoirs. The location, size, and depth of the heat sources that drive the geothermal system can be inferred from P-wave and S-wave velocity and seismic attenuation variations using regional earthquakes and teleseisms. The large-scale regional tectonic regime responsible for the existence of the geothermal phenomena can also be identified, such as a rift system, extensional crustal spreading, subducting plate, or volcanism associated with "hot" spots. Long recording time in reflection surveys (COCORP type recording) can also aid in defining tectonic regime and merging two types of seismic data.

The conventional seismic P-wave and S-wave reflection survey is useful in the detailed definition of structure, fault orientation, stratigraphy, fluid content and state, velocity and attenuation variation, and Poisson's ratio. Estimates of crustal thickness and seismic velocity have been determined in the past by regional seismic refractions surveys. More detailed seismic refraction surveys can map fault location, throw and dip, and Fan refraction-surveys, the 3-D structure of magma bodies.

REGIONAL EXPLORATION

The objective of the regional exploration phase is to 1) perform general reconnaissance over a region measuring in the order 100 X 100 km, 2) identify prospect areas warranting further exploration, and 3) design subsequent surveys leading to a decision of whether to drill a well. If the decision is to drill a well, then the basis for this decision has also determined the optimal location for the well.

The exploration sequence includes the lowest cost surveys per unit area and gradually focuses in on areas deserving more detailed exploration by more expensive surveys as outlined in the previous recommendations. Literature surveys are performed to characterize the geologic and tectonic setting, and photo geology aids in identifying the controlling faults or volcanism which have surface expression. Site confirmations are required to verify these surveys. Geochemical samples are collected and analyzed, and altered zones surrounding various water wells noted. With this background it is possible to plan a regional passive seismic survey to map the regional seismicity and determine gross crustal variations of velocity or crustal thickness.

The hypocenters of microearthquakes recorded in such a survey mark the active fault zones and indicate the level of seismicity that exists. In future prospect studies, microearthquake surveys should be performed with 12-bit, 3 component, multi-station (12-16) arrays. These data would provide a basis for research on the relationship between geothermal reservoirs and microearthquake occurrence. Because of the continued data acquisition and interest by industry users in microearthquakes as an exploration tool, an increase in the cost-effectiveness of this method through improved interpretation techniques and acquisition equipment will have an immediate impact on the geothermal exploration program. Recent equipment development will provide the opportunity to define the existence of the elusive "geothermal earthquake." By defining a uniqueness associated with earthquakes in geothermal regions, especially in Basin and Range prospects, a cost-effective exploration method would be developed. Areas of research should include detailed locations using 3-D velocity models and energy release (in space and time), spectral analyses for source characterization, and V_p/V_s, Q_p/Q_s modeling. These data should then be compared with regional data to detect any anomalous behavior.

Propagation characteristics of P- and S-waves have shown that this technique is useful for detecting velocity and attenuation anomalies associated with hydrothermal alteration, fluid content, structural inhomogeneities, faults, and elevated temperatures. Depending on station spacing and frequency band, P-wave delays are useful for outlining deep, broad anomalies associated with heat sources as well as for near-surface phenomenon such as densification due to hydrothermal alteration and change in fluid content or state. S-wave propagation characteristics are useful for determining Poisson's ratio and fluid content. Surface wave studies should be directed toward inversion for Q as well as S-wave velocity and crustal thickness. These data would provide broad structural control to complement gravity studies.

RESERVOIR ASSESSMENT OF PROSPECT

After the regional reconnaissance surveys have been acquired and interpreted, prospects covering an area approximately 100 km^2 or less are identified, if they exist, which warrant further exploration prior to reaching a decision on drilling a deep well. More detailed and usually more expensive geological and geophysical surveys are conducted, including detailed geological mapping, thermal gradient holes, and electrical surveys. Expensive seismic surveys are cost-effective if it is likely that a well will be drilled.

Multiple coverage seismic reflection surveys provide the best horizontal and vertical resolution of the structure of the region. It is also possible to infer stratigraphy from the location of reflectors and the seismic velocity and attenuation measured for different geologic units. Seismic refraction surveys can be acquired simultaneously "piggyback" fashion with the detailed reflection survey at little additional cost. Refraction surveys are of two types: the in-line reversed profile, and fan profile across the suspected geothermal anomaly. The utilization of true amplitude recording may also permit the mapping of the fluid content in the reservoirs. A problem of critical concern in geothermal exploitation is the permeability of fracture systems. In areas of good quality seismic reflection data, such as the Basin and Range, it may be possible, using the variations in the amplitude of seismic reflections, to distinguish between open fractures and mineralized fractures. Hence the reflection profiling technique is extremely useful in defining structure for optimal well placement and giving an indication of fluid content.

The expected impact of seismic reflection surveys in hastening the assessment of geothermal reservoirs led DOE to acquire several seismic reflection surveys of prospects in southern Utah and northern Nevada under the Industry Coupled Program. These surveys vary in quality and recording mode. At one extreme is a high resolution (frequencies above 100Hz) detailed reflection survey at San Emidio to a "worthless" (according to Ward) single channel weight drop survey. Within the Basin and Range, seismic reflection surveys promise to be extremely valuable. A major and critical component of the recommended program will be the development of improved processing and interpretation procedures to improve the utility of the seismic reflection technique in geologically complex regions where geothermal resources are found.

Microearthquake surveys are the most numerous seismic surveys acquired by industry today. With current improvements in instrumentation they will be recorded with almost the same density of coverage as seismic reflection surveys in areas known to be seismically active. Furthermore, they generate S-waves very efficiently which are extremely difficult to generate in an active survey. They define active faults and anomalous zones of low or high seismicity. They help resolve the velocity and attenuation anomalies associated with high temperature, hydrothermal alteration, or fluid content. Fault plane solutions and spectral source studies define the stress regime acting within the prospect compared to the region.

Measurement of microseismic noise emitted from geothermal reservoirs is in a research mode. The promise of obtaining a direct indication from the geothermal reservoir at a low cost warrants further research. Future surveys must use many more stations on a closely spaced array to avoid spatial aliasing and a recording system with a high dynamic range to separate P-waves emanating from the reservoir from surface waves excited at the earth's surface. A downhole seismometer in an existing well may be the definitive element in resolving the question of the existence of microseismic emissions from geothermal reservoirs.

RECOMMENDED PROGRAM

The Seismic Methods Technical Committee has some recommendations which are not listed as budgetary items. All data acquired by DOE or USGS under the geothermal energy program should be disseminated as raw data and partially processed data to permit the researcher to easily integrate this data into his own data set. Frequently, only the final interpetation of the data is released, making it difficult to integrate different data sets. The raw data should be disseminated rapidly and uniformly, providing all users equal access. An effort should also be made to compile a catalog of existing seismic data including teleseismic P-wave travel time delay and attenuation data, seismicity and microearthquake hypocenters, fault plane solutions, crustal velocity, and attenuation models. A total of 100K per year is provided for an organization to perform this service to the user industry.

The recommended program includes at the highest priority a multi-year effort for laboratory measurement of the properties of reservoir rocks under conditions typical of geothermal reservoirs which can be used to interpret seismic surface measurements. The level of funding is set at $75K/year, though the committee does not have accurate knowledge of the cost of such measurements. The properties should be measured on a wide variety of rocks. The rock properties which must be measured include density, P- and S-wave velocity, and P- and S-wave attenuation under temperature conditions of 100-400°C and pressures of 0-3kb and also higher temperatures near melting or partial melting and appropriate pressures.

The adaptation of the multiple coverage seismic reflection profiling technique to geothermal reservoir assessment requires a multi-year research effort. The acquisition of seismic reflection data can be performed with the conventional equipment used by geophysical contractors. However, the processing and interpretation techniques of this data which are routinely available are baseu on plane horizontal layer geometry typical of sedimentary provinces. Such simple geometrics do not always exist in provinces containing geothermal reservoirs. A major development effort is in the reprocessing and interpretation of portions of existing seismic reflection profiles acquired by DOE. The techniques must treat 3-D structures. It will cost $75K/year for a two year period for two groups to develop the technology for more effectively utilizing this method.

The rapid development of seismic methods for exploration and reservoir evaluation depends on applying a variety of seismic methods to assessing a geothermal reservoir. These seismic techniques should be combined to acquire as many different surveys as possible to minimize acquisition costs. A two year project should be funded to survey the Valles Caldera using all available seismic techniques. The funding of $200K for the first year data acquisition and $100K for the second year analysis, interpretation, and reporting of results is recommended. At least two perpendicular deep seismic reflection profiles should be recorded. The processed record time should be extended from conventional surveys to look deep within the crust in a COCORP fashion. Stationary arrays should be deployed to acquire reverse seismic refraction data of the region as well as for fan seismic refraction data. At night the same instrumentation will be used to acquire microseismic noise data which might be associated with the geothermal reservoir. A detailed microearthquake survey should be recorded across the prospect. Teleseismic and regional earthquakes can be recorded simultaneously and will provide a model of the velocity and attenuation variations deep within the crust. The data acquired in this survey will be interpretated by hypocenter locations to map active faults, velocity and attenuation anomalies, and fault plane solutions related to the stress regime. In addition, it will provide data for long-term basic research on information contained in microearthquake surveys.

A joint DOE-USGS seismic refraction - deep reflection survey is recommended across the Clear Lake Volcano Field. Even though The Geysers has been studied extensively, the source of the system is not well understood. A magma chamber has been identified beneath Mt. Hannah from gravity, teleseismic P-wave delays and teleseismic attenuation. The Clear Lake Volcano Field has high heat flow, yet wells drilled in the area are dry. A detailed reflection survey would aid in understanding the shallow fault structure and possibly the fracture permeability. It would be possible to extend the observations from shallow depths to the source of the system and provide the fundamental information for future location of geothermal systems.

Microseismic noise is the only seismic technique which can in principle directly identify a geothermal reservoir. In the past no definitive tests of the method have been performed in spite of legions of surveys. The survey should use a seismic reflection recording system with a downhole seismometer and can be most easily "piggy-backed" on a seismic reflection survey. The survey must use low-frequency seismometers with close spacing and 50 stations or more in an aerial array. An attempt should be made to purchase the Chevron Beowawe survey. A second survey should be recorded during a DOE reflection for a downhole geophone. If these surveys prove successful, four surveys should be recorded the second year. The acquisition cost is $10K/survey and $5/K for processing.

The geothermal industry is spending a large fraction of their budget on microearthquake surveys. As mentioned earlier, instrumentation is currently being developed to provide digital data in a cost-effective manner. Additional high quality data is needed within the public domain to evaluate the utility of the method. The individual seismograms are needed for the basic research on extracting the most information from this data. This research will have an immediate impact on exploration technology for geothermal reservoirs. A $50K survey is recommended in Dixie Valley the first year which is known to be seismically active, followed by a survey at another prospect the second year.

Regional exploration for geothermal resources relies on microearthquake surveys. Long-term support is required for basic research on extracting the maximum information from microearthquake data which is currently being acquired. Neither geophysical contractors nor the user industry have the manpower for this research, so it should be conducted within universities. Research should focus on more accurate hypocenter location using 3-D velocity models, fault plane solutions, estimating stress drop, energy release, and b-slopes for geothermal regions using the spectra of microearthquakes.

SUMMARY OF RECOMMENDATIONS

By approximate priority -- Items 1-6, first year funding is equal priority.

1) Compilation of all existing regional seismic data.

$100K/year

2) Laboratory measurements of rock properties.

$ 75K/year, 2 years

3) Applied research in processing and interpretation of DOE-acquired reflection data.

$ 75K/year, 2 years

4) Joint seismic experiment at Valles Caldera.

Acquisition	$200K	1st year
Interpretation	$100K	2nd year

5) DOE/USGS Refraction - Deep Reflection survey at Clear Lake Volcanic Field.

(DOE Share)	$125K	1st year
	25K	2nd year

6) Microseismic noise survey

Purchase of Chevron Beowawe Survey (if not already purchased)	$ 10K	1st year
Processing of Beowawe survey	$ 5K	1st year
One additional survey, including deep well seismometer	$ 15K	1st year
Additional noise surveys (Only if justified by above survey results)	$ 15K/survey,	2nd year

7) Detailed microearthquake surveys (Data acquisition)

Dixie Valley	$ 50K	1st year
Second Project	$ 50K	2nd year

8) Basic research on reduction, compilation, interpretation and utilization of microearthquake data (using data from task #7, above).

$ 70K/year 1st to 4th years

Appropriate for Basic Energy Research Funding.

IX

FINAL REPORT

THERMAL METHODS

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of the Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Chandler A. Swanberg (Chairman)	New Mexico State University
David S. Chapman	University of Utah
John Sass	U.S. Geological Survey
Arthur L. Lange	Amax
James Combs	Geothermal Services, Inc.

RELIABLE ESTIMATES OF BOTTOM-HOLE TEMPERATURES DURING THE DRILLING OF DEEP GEOTHERMAL TEST WELLS

Introduction

Present commercial well-logging technology assigns a low priority to the determination of bottom-hole temperatures. One of the primary requirements of geothermal operations, however, is a reasonably accurate estimate of formation temperature at various depths during the drilling process. At depths where there is no appreciable fluid loss at the bottom of the hole, it should be possible to obtain reliable estimates of formation temperature with only minor modifications to existing logging tool design. Primarily, what is required is a rugged electronic thermometer capable of withstanding the temperatures found in geothermal wells (up to 250°C). This thermometer will comprise the leading element of a multiple-function logging tool.

Scope of Work

Develop a temperature module which can be incorporated into geophysical logging tools designed for operation at high temperatures. The temperature module must have the following characteristics:

1. absolute accuracy of ± 0.5 to 1°C;
2. a sensitivity of .01° or better;
3. all downhole electronics must withstand temperatures of up to 250°C or be in a container sufficiently insulated to allow operation at such temperatures for periods of from four to six hours;
4. surface electronics must be rack mounted and compatible with a standard NIMS bin providing temperature readout in real time;

5. the temperature transducer must be the lowermost module of the logging tool;
6. the module must withstand sudden stops of logging tools weighing up to 100 Kg at logging speeds of up to 0.5 ms^{-1} (30 fmp);
7. the temperature response must allow recovery of a step change in temperature within one minute.

Design approval will be required prior to development and testing of the instrument.

Development requirements include repeated tests of mechanical strength, accuracy, and reproducibility in a high temperature (250^{o}C) well. Field tests may be conducted at Phillips Petroleum Company Well 9-1 at Roosevelt Hot Springs near Milford, Utah, or at Well 31-1, or at a well test site with known downhole temperature characteristics.

In lieu of using the Roosevelt facility, the proposal submitted to DOE shall include the known downhole temperature characteristics of the proposed well test site. The proposer should provide documentation that hardware to be used in the field tests have the ability to withstand an environment similar to Well 9-1 at Roosevelt Hot Springs. Publications containing data from Roosevelt Hot Springs are referenced in Appendix A.

ESTABLISH EMPIRICAL RELATIONS BETWEEN THERMAL CONDUCTIVITY AND PHYSICAL PARAMETERS DERIVED FROM STANDARD GEOPHYSICAL WELL LOGS

Introduction

The purpose of this study is to derive empirical relationships between thermal conductivity and other physical parameters such as velocity, porosity, density, etc., that can be obtained from standard geophysical well logs. This type of correlation between thermal conductivity and physical parameters derived from geophysical well logs has been established for sandstones primarily from the geothermal areas of the Imperial Valley. The intent of this study is to determine these correlations for other rock types with emphasis on igneous, metamorphic, and sedimentary rocks from geothermal environments. With the establishment of these empirical correlations between thermal conductivity and physical parameters from standard geophysical well logs, many new heat flow values and thermal properties as a function of depth can be obtained from previously existing boreholes, e.g., oil and gas wells, uranium holes, deep water wells, and geothermal wells which were geophysically logged as well as from newly drilled ones, such as the DOE/DGE industry coupled geothermal wells.

Scope of Work

Develop empirical relations between thermal conductivity and physical parameters derived from standard geophysical well logs. Measure the thermal conductivity of drill cuttings and/or cores obtained from intermediate (300m) to deep (5 km) boreholes that have a suite of geophysical logs run in them. Determine a suite of physical parameters, i.e., porosity, density, sonic velocity, etc., from the geophysical logs. Perform regression analysis on these interrelated physical parameters to establish empirical relations for thermal conductivity as a function of rock type. Perform this type of analysis on several of the DOE/DGE industry coupled geothermal holes in order to confirm the validity of the empirical relations.

Types of Holes

It is not intended that this study be restricted to geothermal wells, rather, oil and gas tests on any other suitably logged wells should be utilized. However, the study does overlap with and would benefit from any proposed study involving coring, logging, and normal conductivity analysis at geothermal wells.

Level of Funding

$60,000 per year for three years.

EFFECTS OF GROUNDWATER FLOW ON THE INTERPRETATION OF THERMAL GRADIENT AND HEAT FLOW MEASUREMENTS

Background

Drilling of shallow temperature gradient and heat flow holes is a fundamental part of all geothermal exploration programs. The importance of these measurements lies in their ability to detect directly the quantity being sought, i.e., heat. However serious limitations on the use of temperature and heat flow information can arise if the measurements are made in a region of poorly understood active groundwater flow. Flow regimes can lead to 1) extremely high and misleading gradients, 2) temperature reversals in the subsurface, and 3) lateral displacement of the near-surface thermal anomaly from deeper reservoirs. Extrapolation of temperature-depth information in such cases is particularly hazardous. This recommendation addresses the field and theoretical studies needed for a better understanding of groundwater flow and its thermal effects in geothermal systems.

Scope of Work

(a) Field Studies. Select several test areas in different geologic settings where simultaneous hydrologic and thermal measurements could be made. Sites where large amounts of exploration data are already available would be preferable. Drill-hole completion methods should be developed to facilitate the measurement of both hydrologic and thermal parameters. Results should be prepared as case studies.

(b) Theoretical Studies. Theoretical studies on the effect of groundwater flow on the thermal regimes of geothermal systems should be supported. These studies should relate to the exploration of geothermal systems and may address any or all of the following:

1. the likely structural control of groundwater flow regimes;
2. interpretation of temperature-depth patterns as diagnostic of flow regimes;
3. temperature increases to be expected with increasing depth in different flow regimes, i.e., the problem of temperature extrapolation;
4. the relationship between shallow aquifers and deeper reservoirs.

Level of Funding

$100,000/year for 5 years.

A SYSTEMATIC PROGRAM OF MAKING ACCURATE TEMPERATURE MEASUREMENTS IN EXISTING WELLS AND BOREHOLES

Background and Justifications

The most cost-effective way to geophysically explore for geothermal resources is to make temperature measurements in holes drilled for other purposes. Currently, tens of thousands of holes are drilled in the United States every year and many of these could be thermally logged for the benefit of the geothermal community. These holes are drilled by various federal, state and local governments, and by private companies. Water wells owned by individual ranchers may also be an important source of information. These holes are rarely if ever routinely logged for temperature and therefore of little use to the geothermal energy industry. This study is aimed at logging these existing wells for temperature and making the data and interpretations available to the geothermal industry. Since this study is regional in nature, it may be suitable for inclusion in the U.S. Geological Survey Extramural program.

Area

The area under investigation is the entire United States including the eastern U.S. where low- to moderate-temperature geothermal resources may exist. Particular emphasis is made on holes located near (50 km) major cities.

Types of Holes

The holes to be logged may include those drilled for base metals, uranium, coal or other minerals, holes drilled for water, oil and gas, or stratigraphic tests or any other purpose. The holes should be at least 100 meters and emphasis should be placed on holes 500 meters or deeper. Emphasis should be placed upon holes located within 50 km of major cities.

Data Required

Discrete temperature measurements every 2 meters (in waters) or 5 meters (in air) for the first 100 meters (5 meters below) measured to a precision of $\pm$ 0.01°C. Measurements of thermal conductivity should be made for holes for which core and/or cuttings and chips are available. In the event that very accurate geophysical logs are available, they should be used to estimate thermal conductivity.

Data Analysis

The data should be reduced to include thermal gradient and, where possible, heat flow. The data should be analyzed with existing heat flow and temperature gradient data to provide national maps of heat flow and temperature gradients.

Scope of Work

Long term effort of 5 years or more (2000 holes/year), at an approximate cost of $500/hole = $1,000,000 per year.

A SYSTEMATIC PROGRAM OF DRILLING SHALLOW (100-150 METERS) AND INTERMEDIATE (500-600 METERS) GRADIENT HOLES

Background

The purpose of this study is to provide temperature-depth data in parts of the country where such data are nonexistent and cannot be obtained by making measurements in existing wells. Several such areas exist in the United States including areas which may benefit greatly from development of low-temperature geothermal resources.

Area

The area to be covered includes the entire United States. The drill holes should be spaced in such a way as to fill the gaps in the "free hole" data. These holes should not be drilled in order to delineate specific geothermal reservoirs, however.

Specifications

The holes should reflect both shallow and intermediate drilling philosophies: i.e., 100-150 and 500-600 meters respectively. The holes should be logged for temperature at discrete 2 meter intervals in water or 5 meter intervals in air for the first 150 meters (5 meters below) to a precision of 0.01°C, and thermal gradient calculated. Samples of cuttings should be analyzed for thermal conductivity, and variable heat flow values calculated.

Level of Funding

Two hundred 100-500 meter holes/year at about $5000/hole for a total of $1,000,000 per year, and ten 500-600 meter holes/year in key areas at about $50,000/hole for a total of $500,000 per year.

DEEP HOLE TEMPERATURE TRANSMISSION SYSTEM

Objective

Numerous deep tests are made each year for purposes other than seeking geothermal resources. Many of these are sealed and abandoned before valid temperature logs can be obtained. In many cases temperature logs are not made. Legal restrictions and liabilities preclude that these wells be left open to permit logging after a period of equilibration. A means of effecting temperature measurements, or at least an equilibrated bottom-hole temperature is needed.

Description

The task might be accomplished by installing one or more expendable transducers in the well prior to sealing. The transducer should be capable of translating temperature by a transmissable signal to be received on the surface at a time or times thereafter. The information may be received on a discrete, programmable schedule, or in a transponder mode (on command). While the means of transmission is not specified (electrical, acoustical or other) the system must meet the following requirements:

a) deliver temperature readings to ± $1^{\circ}C$;

b) perform reliably in an environment of temperature to $150^{\circ}C$ and pressure to 1.5 Kbars at depths to 0.5 km;

c) Transmit at least 3 and as many as 12 times during a period from one month to at least one year following emplacement;

d) Estimated cost of the implant component on a production basis (100 or more units) should be in the range of $1000 or less.

Evaluation

Laboratory tests in a simulated environment matching conditions specified in (b) above will be performed.

Thereafter, tests will be made utilizing retrievable components in at least 3 holes at depths ranging from no less than 30 m to at least 3000 m. Results of the transmissions are to be compared with precision (± $.05^{\circ}C$) temperature logs over a residence time of one year (in the deepest well).

Level of Funding

$100,000/year for 3 years: one year for design and prototype; one year for testing; and one year for production run.

DELETION OF RFP DE-RP07-79ID12040

IN SITU THERMAL PROPERTIES

The thermal methods panel in its 1978 recommendations suggested DOE support of techniques for the determination of in situ thermal properties as one of its long term, low priority items. The level of effort in FY 79 was insufficient to conduct the high priority recommendations, therefore UURI and DOE settled on the thermal properties recommendation and narrowed the scope of the investigation to in situ thermal conductivity for which they allocated $45,000. In the opinion of this panel, the expenditure of the allocated thermal methods funds on such a high-risk, low-priority investigation is not warranted, and more appropriate categories within the Thermal Methods Program are suggested.

X

FINAL REPORT

WATER/ROCK INTERACTION

Technical Review Committee

Geothermal Exploration and Assessment Technology Program

of the Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Wilf Elders (Chairman)	University of California
Robert Bamford	ESL/UURI
John Bowman	University of Utah
Dennis Bird	University of Arizona
Robert Mariner	U.S. Geological Survey
Richard Curtin	California Division of Oil & Gas
Scott Butters	Terra Tek

INTRODUCTION

The panel reviewed the recommendations in the report submitted as the First Report of the Committee, dated December 9, 1977. We are unanimously in agreement with the rationale expressed there for the importance of water/rock interaction studies in any national program of geothermal resource investigations. Such studies form an essential and cost-effective part of any comprehensive scheme of exploration technology. They are equally useful and cost-effective in the reservoir evaluation phase of development and in monitoring the behavior of geothermal reservoirs during production. There are clear dependent relationships between such important parameters as fluid chemistry and enthalpy, and between mineralogy and permeability. Thus, water/rock interaction studies address fundamental characteristics of the phenomenology of geothermal systems. They are therefore, by their nature, eclectic and interdisciplinary in scope, and wide-ranging and effective in their application.

INSTRUCTIONS TO THE COMMITTEE

D. L. Nielson's memorandum to the technical committees listed six general topics for consideration by all technical committees. In addition, he gave us the specific charge to recommend research into the use of chemical and mineralogical indicators in geothermal systems, especially with respect to their application to geothermal exploration and assessment technology. The committee gave earnest attention to all these instructions. However, time permitted detailed consideration of only the specific charge to the committee. Accordingly, the specific recommendations presented below were agreed in detail. Although the general recommendations presented here are believed to represent a consensus of the committee, the text is based only on the chairman's notes and may not reflect the views of all members of the committee.

GENERAL RECOMMENDATIONS

Our committee criticized strongly the major unbalance between the level of effort and expenditure between geophysical, geological and geochemical approaches to the mission of the Exploration and Assessment Technology Program. Geology and geochemistry are poorly funded relative to their importance and effectiveness in achieving the goals of the program. Furthermore, we feel that some of the more expensive, competing projects, previously supported, or currently proposed, have less relevance to programmatic needs. Applying poorly understood exploration techniques to little known targets must be avoided, particularly in view of the limited funding available.

We recommend that this imbalance in support be immediately corrected and that a greater level of funding be expended on water/rock interaction and the related topics which support the overall mission of the program. As the utility and effectiveness of these approaches continue to be demonstrated in the future, we confidently expect the proportion of funds allotted to them to grow. This could be achieved by eliminating too expensive and less successful competing projects in exploration and assessment technology.

Our second criticism concerns the apparent lack of continuity in programs and funding. To a large extent this appears to be due to instability in the organizational fabric of the Division of Geothermal Energy. Although change permits improvement, it does not ensure it. Changes which occur more rapidly than their effects can be monitored are wasteful and chaotic. The effect at the operational level is disasterous. Hastily conceived short-term projects addressing only short-term goals are expensive, wasteful and deleterious to the development of personnel and facilities. We recommend that the Division identify techniques and areas promising the best returns, and formulate plans for long-term funding for them. Projects which have had sufficient time to mature and which have shown <u>not to be</u> successful or cost-effective, in terms of the programmatic needs, should be ruthlessly eliminated. For successful programs, sufficient continuity from year to year is required to permit them to reach their optimum. The RFP and PRDA mechanisms may have to be adjusted to reflect these needs for continuity.

The following general recommendations follow the format of the general topics put to all the Technical Review Committees in D. L. Nielson's memorandum outlining the objectives of the Marina Del Rey conference:

<u>Topic 1</u>. The near-, mid-, and far-term objectives of the DOE/DGE Exploration and Assessment Technology and Reservoir Engineering Programs.

<u>Response</u>. The aims of both programs should be to provide the concepts, models, methods, data and tools for exploration, assessment, or reservoir engineering. The actual exploration, assessment and reservoir engineering will be carried out by industry. In other words, <u>these</u> programs within DGE should <u>not</u> be performing exploration, assessment, and reservoir engineering, except in so far as doing so assists in the development and improvement of the science and technology of these activities. The outcome of these developments

and improvements should be communicated rapidly to the industrial users of the technologies concerned.

In the short-term, the aim should be to understand the nature of geothermal reservoirs of various types. We should concentrate on geothermal fields which have been extensively explored by drilling. Unproved exploration or assessment techniques should only be tested in such an environment. Better known and established techniques of exploration can also be refined and calibrated best where the nature of the target reservoir is already known.

In the mid-term, the body of heuristic techniques and empirical observations resulting from the program should be synthesized into a format useful to industry and a hierarchy of strategies developed in terms of their utility, generality, and cost-effectiveness.

In the long-term, there should be developed a body of concepts, theory, and analysis which will serve to explain and rationalize the proceeding observations and methods. These unifying principles will guide development of new technology and improve the old. Finally there should be a thorough program of education to put into practice what has been learned.

Topic 2. The effects of the National Energy Act.

Response. Our committee felt that we lack competence to discuss this issue. We recommend that all future committees include industry members.

Topic 3. An outline scenario for the best overall DOE program in exploration and assessment technology, at the $2.5M and $5M level.

Response. The scenario of the DOE program should be based on (a) balance and (b) continuity. A hard look should be directed toward the cost-effectiveness of various competing technologies in Exploration, Assessment and Reservoir Engineering. We feel that such an analysis would justify spending up to 20% of the budget of these programs on water/rock interaction, as broadly conceived, over the next five years.

Topic 4. Geothermal Exploration and Assessment Technlogy for low- and moderate-temperature resources.

Response. Our specific recommendations include work on these resources.

Topic 5. Rock properties measurements.

Response. Several committees referred to the need for further work in this area, as do the specific recommendations of this committee. We feel that there is also a need to document and make available existing data in this field pertinent to geothermics. We note also that large sums have been appropriated for this topic by the Energy Technology program in the hydrothermal geosciences. There is therefore a need for DOE to coordinate research in this area being carried on under different programs, in order to prevent duplication and redundancy.

Topic 6. Transfer of technology development to industry.

Response. We feel that there already exists a considerable body of data and techniques of great relevance to the problems faced by industry, which is not being utilized because of failures in communication. We recommend, therefore, that technology transfer should play an increasingly important role in the activities of DGE. Workshops, symposia, proceedings volumes, reports of case studies, and instructional manuals are needed.

FY 80 IMPLEMENTATION
SPECIFIC RECOMMENDATIONS

Introduction

The committee felt very strongly that a broad-ranging and well-focused program on water/rock interaction is necessary. It must, at the same time, involve direct studies of the nature of geothermal systems and investigations of the fundamental controls over the processes occurring within them. Only in this way can the industry have the appropriate scientific basis on which to make intelligent and informed decisions.

Our proposal therefore has three elements: (1) resource and exploration target definition, (2) basic science support and development of applications, and (3) technology transfer. These have equal priority although greatly disparate funding levels.

PROJECT 1

Topic. Identification, description and interpretation of the characteristic signatures of water/rock interactions and their systematic variations in recording fluid flow and thermal history in active hydrothermal systems.

Level of Funding. $600,000/year (Level funding for several years).

Justification. In order to explore intelligently, we need better definition of exploration targets. Such studies will also provide the scientific underpinnings for reservoir assessment, reservoir engineering and field management.

Specific Approaches. A PRDA should be issued requesting such basic studies of subsurface mineralogy, petrology and geochemistry in specific geothermal reservoirs for which adequate surface geophysics exist and which have been drilled adequately so that the nature of the resource is known and reasonable subsurface sampling exists.

The approach should be broadly integrative and use a variety of techniques. It could include studies of hydrothermal mineral zoning, isotopic and chemical analyses, geothermometry and studies of physical properties of rocks. The aim would be to study these parameters in three dimensions and to investigate how these reservoir evolved in space and time. This can only be achieved in fields where drilling is adequate. These results can then be compared with the surface signature to test various surface geothermometers, vectoring techniques and other exploration methods. Attention must also be given to developing the appropriate techniques of sampling gases, fluids and solids both in the wells and at the surface.

The studies may involve studies of some fields which have not yet been well characterized from the point of view of water/rock reactions, but for which drill samples exist, or may involve the improvement and development of on-going projects on fields which have been better investigated. The fields chosen should include a range of high to low temperatures, and of different rock types, fluid chemistry and fracture control.

PROJECT 2

Topic. Study of rock and fluid properties.

Level of Funding. $200,000 (probably increasing in future years).

Justification. Such studies are necessary if we are to understand the nature and dynamics of fluid flow and permeability in hydrothermal systems. The findings would be immediately applicable to reservoir engineering, and problems of self-sealing, scaling and production decline, and of reinjection.

Specific Approaches. A PRDA should be issued inviting the development of models concerning the variations of permeability in space and time in geothermal reservoirs. They may be based upon new or existing data. The task could involve measurement of permeability and fracture conductivity, and other relevant parameters, as a function of time in production aquifers. These measurements could then form a basis for analysis and modelling of heat and mass transfer and the effects of water/rock interaction on the physical properties of rocks. This may involve a combination of field, laboratory and theoretical approaches to understanding the important features such as those controlling production decline and injectivity changes.

PROJECT 3

Topic. Improvement and development of geothermometers.

Level of Funding. $175,000/yr (gradual increase in future years).

Justification. Geothermometers are useful, cost-effective and poorly understood exploration tools, which are commonly misapplied. There is a need to develop new and refine old methods, and to put them on a sound basis of theory.

Specific Approaches. A PRDA should be issued on the general topic of geothermometry requesting the development, refinement, improvement and testing of various geothermometers. Solute, isotopic, organic and radiogenic methods could be included. They should apply to high and low temperatures. Specific input on the chemical, thermodynamic, and kinetic controls of the geothermometers should be sought. Such an approach will develop new families of geothermometers and put limits on the applicability of existing ones.

PROJECT 4

Topic. Technology transfer of water/rock interaction studies applied to geothermics.

Level of Funding. $50,000 (increasing in future years).

Justification. A great deal of theoretical, experimental and observational studies have been made on water/rock interaction which are pertinent to geothermics. The successful application of these concepts derived from geochemistry, petrology, hard-rock mining, solution mining, and radioactive waste disposal is hindered by failures in communication.

Specific Approaches. A RFP should be issued to support conferences or workshops on water/rock interactions in geothermics. This should facilitate two-way communication on methods, theories, applications and case histories of geochemical approaches to problem solving. These meetings should be followed by multi-authored manuals to document and disseminate the ideas and data which result. Industry participation would be an essential component.

FURTHER SPECIFIC RECOMMENDATIONS

(1) DGE should provide funding for obtaining cores in wells being drilled by industry and for the curation and study of the materials so obtained. A certain flexibility is necessary here to respond to opportunities which arise due to industry drilling decisions. An announcement might be issued inviting those drilling geothermal wells to participate. Acquisition of such cores is imperative to many programs.

(2) The scope of this committee is so broad that we feel its task should be divided between at least two committees. There was disagreement on the best form of the division. In any case, industry participants should be included in new committees.

XI

FINAL REPORT

RESERVOIR ENGINEERING

Technical Advisory Group

Geothermal Reservoir Engineering Management Program

of Department of Energy/Division of Geothermal Energy

May 14-16, 1979

Marriott Inn

Marina del Rey, California

Contributors:

Leland Roy Mink (Chairman)	DOE/ID
Don Campbell	Republic Geothermal, Inc.
Jack Howard	UC/LBL
Gil Cady	General Crude Oil Co.
Subir Sanyal	Stanford University
Myron Dorfman	University of Texas
Ahmed Abou-Sayed	Terra Tek Inc.
Ted Glenn	ESL/UURI
Marty Molloy	DOE/SAN
George Frye	Aminoil USA
Ron Schroeder	LBL
Marshall Reed	DOE/Washington, D.C.

INTRODUCTION

The committee was concerned about the uncertainty of the management structure of the Division of Geothermal Energy. The organization in Washington has been shifted around several times recently with several changes in project management. This has led to confusion with respect to the goals of the Geothermal Programs not to mention apparent confusion within several national programs. The committee emphasized that more coordination between the national programs needs to be conduced at all levels. The inclusion of the reservoir engineering group in the Geothermal Exploration and Assessment Technology Program meeting is a good start. Discipline oriented coordination rather than project oriented coordination will result in a more cost-effective and productive DOE/DGE program.

INTERACTION WITH OTHER DGE PROGRAMS

The reservoir engineering group discussed related progress where interaction and coordination with the reservoir engineering program should be emphasized. These programs are 1) Log Interpretation, 2) Logging Instrumentation Development, and 3) Exploration and Assessment Technology.

The Geothermal Log Interpretation Program should provide emphasis on identifying production logging techniques in addition to exploration borehole logging techniques. The major need of the reservoir engineer is interpretive criteria for logs obtained during production and/or production testing. This could be accomplished through the better understanding of temperature, pressure, flow meter and bond logs in high temperature and two phase flow environments. Also, the interpretation of logs through igneous and metamorphic lithologies needs to be improved. A program involving case studies of geothermal system which could be addressed under development or in production was recommended. Another need which falls under the Geothermal Log Interpretation Program is that of correlating cores and logs from geothermal areas. The value of core in log interpretation techniques cannot be over emphasized. It is recognized that obtaining core is expensive and often risky. The Reservoir Engineering Committee recommends the Industry Coupled Studies Program be re-instated emphasizing the need for core and logs from geothermal wells of opportunity.

The Geothermal Logging Instrumentation Development Program is progressing very well with respect to meeting the needs of the reservoir engineer and interfacing with industry. Temperature limitations of the cable along with limitations of various tools such as caliper and flow meter were identified as problems and are presently being worked on. As emphasized earlier, the need of the reservoir engineer is for production logging capability. This requires the instruments to be in the well during production testing often for rather long periods of time.

The specific tools which are needed for production logging are temperature, pressure and flow metering tools. Other tools which are needed by the reservoir engineer include salinity, porosity, fracture location and orientation and lithologic determination tools.

Proceedures and techniques being developed under the Geothermal Exploration and Assessment Technology Program can make important contributions to the Reservoir Engineering Program. A long term goal should be the development of reliable downhole sampling, measuring and/or chemical logging techniques to give reliable fluid chemistry information. This would help in the identification of fluid boundaries and/or fluid entires into a borehole. The major problem lies with concentration of solids in the geothermal systems upon production which leads to the need to accurately model scale precepitation phenomena.

The geophysical techniques used in exploration and being developed under the Exploration and Assessment Technology Program should be applied to help define the extent of the reservoir. This would help speed up development by placing more reliability on the size and extent of a geothermal reservoir. The refinement of the geophysical methods for reservoir definition may be more valid than for resource exploration at this time. Therefore, it was recommended that the Exploration and Assessment Technology Program look at the use of geophysical techniques for reservoir definition.

RESERVOIR ENGINEERING

The needs of the geothermal reservoir engineer are outlined in the GREMP Program with a few modifications. Much of the recommended work outlined in 1978 is being conducted at the present time within the GREMP Program.

It was pointed out that the Reservoir Engineering Program should be better coordinated with the other programs. Much of the work needed within reservoir engineering has been assigned to various other national programs. A yearly conference involving all the major geothermal programs may be the answer. A yearly conference would result in more industry involvement since it would be only one meeting instead of several specialized meetings by each of the major programs.

The objective of the Reservoir Engineering Program was discussed and was defined as the need to provide increased accuracy in prediction through the development and 'sharpening' of techniques. The coordination of a full field project from exploratory drilling through development has been the responsibility of the reservoir engineer. The final output expected from the reservoir engineer is a reserve analysis for a given geothermal prospect.

An area which had been initially identified as critical for reservoir engineering was that of rock properties. Recent decisions have resulted in rock properties not being a major national program. The reservoir engineering committee feels the Reservoir Engineering Program should identify rock properties as a new initiative. Measurements should be conducted on specific core samples to better evaluate the logs and better understand the producing formations. Mechanical rock properties are most important to the reservoir engineer; but electrical, accoustic and thermal properties are also required, particularly if geophysical techniques are to be used to aid reservoir definition. These properties should be measured as near to in-situ conditions as possible.

The understanding of two phase flow was identified as a critical need for the reservoir engineer. It was recommended this be a principal task under the subheading of Well Testing. It is apparent there is a need to be able to interpret well test or production data when flashing occurs in a wellbore or in the formation . This involves better measurement techniques at the surface to detect subsurface conditions. It was recommended that interface occur with the chemical and nuclear industry to assist in addressing some of the problems. As mentioned in the instrument development section, there is a need for continuous monitoring of flow with reliable accurate results.

Modeling was discussed at length and overall agreement is that numerical modeling should receive a high priority for future funding. Analytical modeling is at a point now to satisfy present needs. Physical modeling does not appear to satisfy the complex needs of a geothermal reservoir model. Model comparison and validation should be a new initiative in the Reservoir Engineering Program. An attempt should be made to try all major codes on the same system and compare results with respect to output and efficiency of the code. It was suggested the codes should be run on an actual geothermal system where adequate data exists rather than a hypothetical situation. Suggested areas which could be used for code comparison include Cerro Prieto, Mexico; Wairakei, New Zealand; or Larderello, Italy. A workshop should then be held on the use and limitations of the various codes available; LBL should do this task as part of their in-house work.

The present GREMP Program appears to be addressing the problems outlined in the previous Steering Committee Meetings. In light of FY-80 budget restrictions, several areas could be funded at a reduced rate, and new initiatives be limited.

The LBL work should emphasize industry interface. Possibly cost-sharing reservoir engineering work with industry on case studies projects would allow a continued level of effort for LBL as well as other national labs. Work on the SHAFT code should be oriented toward refinement of fracture analysis and streamlining the code so it would be more usable to industry.

The Cerro Prieto Project should be continued emphasizing the interpretation of the data collected and continued collection of production data. A summary addressing drilling, completion, testing and stimulation of Cerro Prieto wells would be very helpful to industry.

Support to academic institutions should be continued to provide training of future geothermal reservoir engineers. Stanford and University of California at Riverside are doing very significant work and should be supported in their present roles. Other areas of support should be examined for the University of Colorado and Princeton University. If more funding were not identified, a possible reduction in the Stanford Italian Project and Radon Tracer Studies may be necessary.

With respect to subcontracts within the GREMP Program, all on-going activities should be supported as planned except for the Decline Curve Analysis Task. This task should be funded with FY-79 money with an attempt to speed up the contract and gain a product this fiscal year. It was felt the project should not extend into FY-80 because of budget limitations. No new starts were anticipated in FY-80 because of budget limitations although the comparison of various codes should be initiated if funds were identified. Additional funds should be identified for initiating work in the area of two-phase flow phenomenon. This was described as an essential need for geothermal reservoir engineering.

National Energy Act

Several comments were presented in the reservoir engineering group relating to the National Energy Act. The information on the Act needs to be effectively disseminated. This could be accomplished through an education program by DGE or by a non-government group such as GRC. The information needs to be explained to the economic advisors and vice presidents of the various companies rather than to the engineers and technical people. A problem with the Energy Act appeared to involve the recapture provision with respect to returns on investment. The 10% investment credit until 1982 is too short a time. Unless a resource was already drilled and ready to develop, a given project could not be completed by 1982. It was felt another five years needs to be added to the time frame to be realistic for new geothermal prospects. It was pointed out the recapture and phase out provisions were counter-productive in the eyes of industry. Other areas which should be considered were intangible drilling costs, completion, temperature tax credit, and wheeling provisions.

In all the group agreed the National Energy Act will benefit geothermal development, but needs some tailoring to be an effective stimulant.

FY 1979

RESERVOIR ENGINEERING PROGRAM

LBL: Cerro Prieto Case Study

Total $531,000 — Spent to 2/1/79 $133,000

A. Coordination, publications, meetings. $91,000

B. Data collection and analysis for geology. $120,000

C. Geophysics surveys (some done yearly). $120,000

D. Well testing and analysis. $60,000

E. Chemistry study of water for reinjection. $85,000

F. Modeling reservoir behavior. $55,000

LBL: Coso Hot Springs Well Testing

Total $33,000 — Finished 12/31/78

LBL: East Mesa Reservoir Simulation

Total $28,200 — Finished 12/31/78

LBL: Larderello, Italy Reservoir Simulation

Total $135,000 — Spent to 2/1/79 $36,300

LBL: Klamath Falls Reservoir Testing

Total $88,800 — Expenditures?

LBL: Reservoir Engineering Research

Total $225,000 — Spent to 2/1/79 $106,500

A. Two-phase reservoir model, SHAFT -78

B. Variable rate, multiple well, reservoir testing

C. Modeling heat and mass transfer in fractured reservoir

D. Modeling transient flow in wellbore

FY 1979

RESERVOIR ENGINEERING PROGRAM

LBL: Management of subcontracts

<u>Total $250,000</u> Spent to 2/1/79 $72,500

Management of subcontracts.

Publication of reports.

Host meetings on program development.

Subcontracts through LBL

<u>Total $1,065,000</u> Spent to 2/1/79 $560,000

A. Stanford University: Modeling, tracer, and analytical studies, and annual workshop. $180,000

B. Stanford University: Italian Project; data compilation and analysis. $35,000 (costed in '78)

C. System, Science, and Software: Wairakei reservoir model. $89,000

D. Princeton University: Mass, heat fracture model. $54,000

E. Univ. Calif, Riverside: Cerro Prieto geochemistry and mineralogy $158,000

F. Measurement Analysis Corp: Measurement of reservoir parameters. $4,000.

G. Terra Tek: Annotated bibliography of reservoir of reservoir engineering $21,000

H. Battell P.N.L. : Development of geothermal testing. $41,000 + $80,000

I. Terra Tek: Instrument to measure non-condensable discharge. $62,000

J. Intercomp: Analytical techniques to interpret 2-phase flow. $118,000

K. Republic Geothermal: Mineral deposition in the reservoir. $72,000

L. RFP on Decline Curves $100,000

M. RFP on Geochemical Tracers $130,000

U.S.G.S.: Cerro Prieto Case Study

Total $89,000

A. Fluid Chemistry Studies. $50,000

B. Subsidence Research, leveling survey. $14,000

C. Trilateration Survey. $25,000

XII. SUMMARY

Recommendations from the Marina del Rey conference are summarized in Table XII.2. Copies of the reports were sent out to a number of exploration program managers in industry for their review. It was requested that these individuals help set priorities for funding. Although few responded to this request, those recommendations will be used to assign priorities for FY80 procurements.

The variety of exploration methods currently being used by industry is remarkable. Although several companies have standardized their exploration procedures and utilize only selective methods, the majority apply a large number of survey types, with strong emphasis on geophysical surveys. The report of the Exploration Architecture committee (section VI) reviews the various procedures used and cites evaluations of these methods by industry. However, it is apparent from the review of this document by industry managers and from talking with exploration personnel from various companies that even within companies there is presently a diversity of opinion about the usefulness of individual exploration tools in specific environments. And as more data becomes available, it is clear that procedures that work quite well in, for instance the Salton Trough, may be of little use in the Basin and Range. Thus it is clear that continued evaluation of various techniques in different environments can have a significant impact on the efficiency of geothermal exploration in the U. S.

The Exploration Architecture committee has also re-emphasized some of the differences that will exist between the exploration procedures used for

TABLE XII.1

SUMMARY OF RECOMMENDATIONS OF TECHNICAL REVIEW COMMITTEES OF THE GEOTHERMAL EXPLORATION AND ASSESSMENT TECHNOLOGY PROGRAM AND THE TECHNICAL ADVISORY GROUP OF THE GEOTHERMAL RESERVOIR ENGINEERING MANAGEMENT PROGRAM.

COMMITTEE	RECOMMENDATIONS	PRIORITY	FUNDING	DURATION
STRUCTURE, STRATIGRAPHY, AND IGNEOUS PROCESSES	1. Surface Geology -detailed geologic mapping -aerial photography	1	225K/yr	5 yrs
	2. K-Ar Dating --to refine models of relationship of magma systems & geoth. systems.	2	75K/yr	5 yrs
	3. Subsurface Studies Structural	3	40K/yr	
	Gravity (3 surveys/yr)		105K/yr	5 yrs
	4. Rock Properties	4	30K/yr	
	5. Igneous Studies Models of magma system evolution - chemistry.	5	155K/yr	3-5 yrs
EXPLORATION ARCHITECTURE	1. Refinement of MT		250K/yr	
	2. Groundwater effects on thermal measurements		100K/yr	
	3. Regional fluid geochem		100K/yr	
	4. Regional gas geochem		100K/yr	
	5. K-Ar dating - regional		100K/yr	
	6. Joint collection and inversion of data.		50K/yr	

COMMITTEE	RECOMMENDATIONS	PRIORITY	FUNDING	DURATION
ELECTRICAL METHODS	1. EM modeling & inversion	1		
	a) cost-effective 2D & 3D modeling programs		300K/yr	3 yrs
	b) alternate inversion schemes		100K/yr	3 yrs
	2. Controlled source EM field studies	2	100K/yr	2 yrs
	3. Rock Properties	3	200K/yr	3 yrs
	4. Regional MT map	1	50K/yr	2 yrs
	5. Calibration sites & procedures	2	60K/yr	1 yr
	6. MT Workshop	3	20K/yr	
	7. Testing of following (no budget recommendation provided): -Induced Polarization -Magnetometric Resistivity -Long array MT -Singular coincident loop TPEM.			
WATER/ROCK INTERACTION	1. Mineralogy, geochemistry, + petrology in geothermal reservoirs.		600K/yr	2 yrs
	2. Workshop on water/rock in geothermics		25K/yr	
	3. Rock + fluid properties		200K/yr	2 yrs
	4. Geothermometers		175K/yr	2 yrs
	5. Obtain core			

COMMITTEE	RECOMMENDATIONS	PRIORITY	FUNDING	DURATION
THERMAL METHODS	1. Bottom hole T during drilling			
	2. Relations between thermal conductivity and physical parameters		60K/yr	3 yrs
	3. Effects of groundwater flow on thermal measurements		100K/yr	5 yrs
	4. "Free hole" Program		1000K/yr	5+ yrs
	5. Shallow & intermediate depth drilling		1500K/yr	
	6. Deep hole T transmission system.		100K/yr	3 yrs
SEISMIC METHODS	1. Data compilation and dissemination	1	100K/yr	
	2. Rock properties	2	75K/yr	2
	3. Research in processing & interpretation	3	75K/yr	2
	4. Seismic @ Valles Caldera	4	200K 100K	1st year 2nd year
	5. Clear Lake Survey	5	125K 25K	1st year 2nd year
	6. Microseismic noise @ Beowawe	6	30K 15K	1st year 2nd year
	7. Microearthquake	7	50K 50K	1st year 2nd year
	8. Basic research on microearthquake processing & interpretation	8	70K/yr	4 yrs

COMMITTEE	RECOMMENDATIONS
Reservoir Engineering	1. Geothermal Log Interp. Prog. should study production logging techniques. 2. Obtain core 3. Development of techniques to provide reliable fluid chemistry. 4. Test geophysical exploration techniques in defining extent of reservoir. 5. Better coordination with other programs. 6. Rock properties. 7. Understand 2 phase flow. 8. Refine numerical modeling-comparison of available codes. 9. Emphasize industry interface (cost sharing) 10. Continue Cerro Prieto Project. 11. Support academic institutions training reservoir engineers. 12. Support GREMP subcontracts. 13. Complete Decline Curve Analysis Task this year.

high-temperature environments versus those for intermediate- to low-temperatures environments. They have emphasized that the value of the individual systems will dictate the use of the less expensive exploration procedures, largely geology and geochemistry. An additional consideration will be the cultural interferences inherent in exploring for a resource in the proximity of a user. Since few exploration case studies of low- to moderate-temperature hydrothermal systems exist in the literature, and given that there are few private groups involved in the exploration for these systems, the Geothermal Exploration and Assessment Technology Program will become more involved with these resources in the future. The direct applications of geothermal energy can have a tremendous impact on the nation's efforts to conserve its fossil fuel resources and reduce the use of foreign imports.

ACKNOWLEDGEMENTS

This work was supported by the Department of Energy, Division of Geothermal Energy under contract DE/AC07-79ET27002.

The efforts of S. H. Ward, P. M. Wright, H. P. Ross, W. E. Glenn, W. Forsberg, and S. M. Moore of ESL/UURI and R. Gray, L. L. Mink and M. Reed of DOE are gratefully acknowledged. We also wish to acknowledge the efforts and contributions of the members of the technical review committees of the Geothermal Exploration and Assessment Technology Program and The Reservoir Engineering Technical Advisory Group.

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1980—640-258/2359