Earth Sciences Division

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Geothermal Reservoir Engineering Management Program Plan (GREMP Plan)

October 1977

Prepared for the U.S. Department of Energy
Office of Energy Technology
Division of Geothermal Energy

by the

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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INTRODUCTION

The Lawrence Berkeley Laboratory (LBL) has been assigned the task of developing and implementing a comprehensive plan for support of research in geothermal reservoir engineering in the broadest sense, for the Division of Geothermal Energy (DGE), Department of Energy (DOE). Development of this plan entails identification of major elements bearing on geothermal reservoir research; implementation will be by means of contracting with qualified groups to perform research on these identified elements.

A Program Planning Team having members with broad experience in the field was formed to identify the desirable elements of geothermal reservoir research and to develop a program plan. A Review Task Force was separately formed to review and make recommendations for improvements in the program plan. The members of the Program Planning Team and the Review Task Force are listed below with their institutional affiliations.

The Program Planning Team

C. H. Bloomster, Battelle-Pacific Northwest Laboratory
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R. C. Schroeder, LBL

W. J. Schwarz, LBL

T. L. Simkin, LBL

C. F. Tsang, LBL

P. A. Witherspoon, LBL

The Review Task Force

J. H. Barkman, Republic Geothermal Company

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W. B. Brigham, Stanford University

R. L. Christiansen, United States Geological Survey

G. L. Frye, Aminoil, USA, Inc.

M. S. Gulati, Union Oil Company

P. N. La Mori, Electric Power Research Institute

J. C. Martin, Chevron Oil Field Research

C. W. Morris, Phillips Petroleum Company

G. F. Pinder, Princeton University

H. J. Ramey, Stanford University

The resulting program, incorporating the recommendations of the Review Task Force and designated as the Geothermal Reservoir Engineering Program (GREMP), is presented in this document.

Management Responsibilities

Management of the LBL GREMP effort is the responsibility of Dr. J. H. Howard and Werner J. Schwarz, with Dr. Paul A. Witherspoon, Associate Director of LBL and Division Head of the LBL Earth Sciences Division, acting as Principal Technical Advisor. Management for the Department of Energy, Division of Geothermal Energy effort is the responsibility of Dr. John W. Salisbury, Chief, and Dr. Leland L. Mink, Program Manager of the Resource Exploration Assessment Branch.

Mission of Division of Geothermal Energy

The mission of the Division of Geothermal Energy is to stimulate the development of geothermal energy as an economic, environmentally acceptable, and reliable source of energy. Toward this end the Division's work is allocated principally between the Directorate for Research and Advanced Technology and the Directorate for Resource Utilization. The near- and mid-term goals of the Division of Geothermal Energy and these directorates are commercial development of the nation's accessible geothermal resources, and establishing commercial viability of the more abundant but less tractable advanced geothermal resource types, respectively.

Objective, Development, and Planning of GREMP

The objective of the Geothermal Reservoir Engineering Management Program (GREMP) is to establish an improved capability to exploit geothermal resources. Research elements are being planned to answer such fundamental questions as 1) how large is a particular resource, and 2) what is the spatial distribution within it of temperature, porosity, permeability and other parameters. When these data are obtained the next question of primary importance concerns the future behavior of the geothermal reservoir under exploitation. The ultimate goal is to develop technically feasible plans for the economic exploitation of given geothermal reservoirs with a high degree of reliability.

The development of a GREMP plan has included: 1) the assessment of the present status of geothermal exploitation engineering (with special attention to the needs of the practitioner), 2) the identification of needs for improvement of this status, 3) the formulation of a plan of action to achieve such improvement. The latter will include a) appropriate research projects with their schedules and milestones, b) priorities based on the need for results and c) as complete and specific an explanation of proposed research projects as possible.

The planning process for GREMP involved: 1) organization of the Program Planning Team and Review Task Force, 2) a literature survey, 3) evaluation of the state of the art, 4) identification of needs for research, 5) definition of the research projects, 6) acquisition and incorporation of Review Task Force recommendations, and 7) publication of the GREMP planning document. A planning schedule is given in Fig.1.

This document describes the development portion of GREMP. After final publication, implementation will be initiated by the selection of subcontractors to perform the research work. This work will be monitored by LBL.

The Six Major Research Elements

Six major elements were identified to make up the research program structure. These are:

Properties of Materials
Definition of Reservoir Characteristics
Description of Example Reservoirs
Modeling the Behavior of Geothermal Systems
Exploitation Strategies
Economics

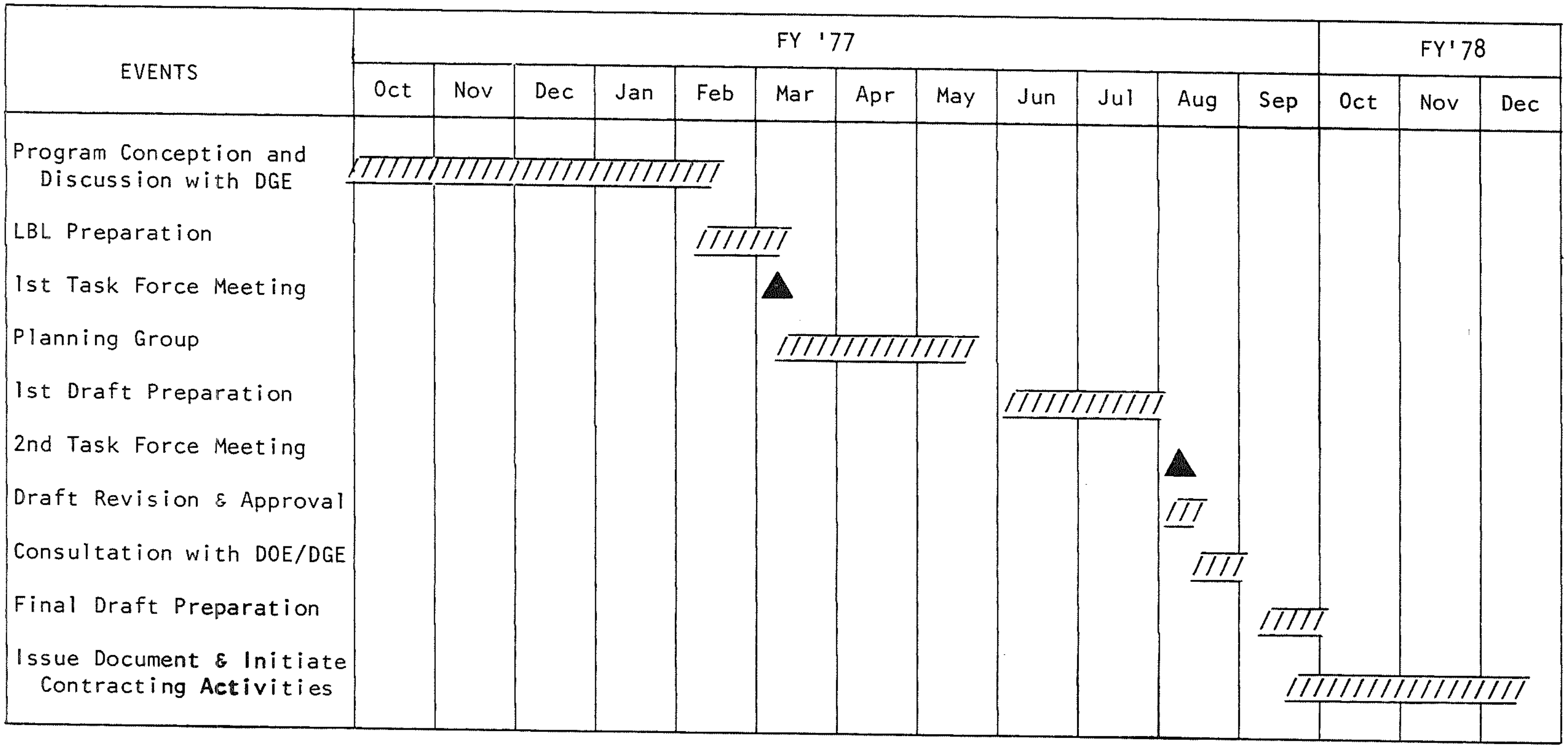

Figure 1. GREMP planning schedule.

These major elements may be subdivided into several levels of organization. These levels, in descending order, are the research category, research project, and individual task. The geothermal reservoir engineering program's six elements yield twelve research categories and fifty research projects. These are discussed in detail in Appendix A and summarized in Table 1.

Research Program Integration

The scheduling of research projects was performed with research program integration in mind, that is, maximum opportunity was provided for using the results of one research project to aid in other research project efforts. Figure 2 is an overview of the research program providing a sense of interrelationships in the research categories. It gives a perspective of the value of research results derived from each category. The ultimate goal of this document is to assist in developing the means for providing exploitation plans that are technically feasible, practically possible, and financially attractive.

GREMP Coordination With Other Geothermal Programs

During the proposal and contracting stages of GREMP, LBL will continue to maintain a close liaison with all Federal and State organizations to help coordinate all work performed in identical or similar fields. We will especially coordinate the programs funded by DOE, Division of Physical Research and Division of Geothermal Energy; the Geothermal Logging Development Program at Sandia Laboratories; the Geothermal Log Interpretation Program at Los Alamos Scientific Laboratory* (LASL), and the USGS Geothermal Program. Liaison will

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*Final definition and then implementation of Project II-D, Interpretive Borehole Geophysics, has been assigned to LASL by DOE-OET/DGE.

Table 1. Summary of the elements, categories, and projects of the GREMP plan.

RESEARCH ELEMENT	RESEARCH CATEGORY	RESEARCH PROJECT
I. Properties of Materials	1. Properties of Materials	1. Simultaneous measurement of electrical conductivity, acoustic velocity, compressibility, thermal expansion, porosity, permeability, and the effects of fractures on permeability, porosity, etc. in rocks saturated with saline solutions at elevated temperatures, various pore pressures, and differential stress status.
		2. Simultaneous measurement of thermal conductivity and heat capacity in rocks saturated with saline solutions at elevated temperature and pressure.
		3. Effect of solutes at saturated values on long-term behavior of physical properties of rocks at elevated pressure and temperature.
		4. New techniques.
II. Definition of Reservoir Characteristics	A. Surface Geophysics	1. Evaluation of existent techniques - - gravity.
		2. - active seismic methods.
		3. - passive seismic methods.
		4. - electrical and electromagnetic techniques.
		5. - heat flow.
		6. Support for new geophysical techniques.
		7. Review of combinations of geophysical techniques.
		8. Research into improved geophysical methods for exploitation purposes.
II. Definition of Reservoir Characteristics	B. Interpretive Borehole Geophysics	1. Improve economic and institutional framework.
		2. Define parameters of value and interest.
		3. Improve and ruggedize logging tools.
		4. Establish and operate calibration wells.
(LASL responsibility)		5. Conduct appropriate laboratory experiments related to log interpretation.

Table 1, cont'd.

II. Definition of Reservoir Characteristics (cont'd)	B. Interpretive Borehole Geophysics (cont'd)	6. Establish data bank of logs, cores, cuttings, fluid chemistry, and well performance. 7. Develop interpretive techniques for data collected from logging; anticipated parameters of interest are net pay, pore geometry, porosity, permeability, temperature, pressure, thermodynamic fluid quality, fractures present, matrix heat capacity, concentrations of selected chemical species, presence of certain gases. 8. Disseminate results of program.
II. Definition of Reservoir Characteristics	C. Well Testing	1. Assess conditions in geothermal reservoirs that affect tool and analysis requirements. 2. Improved data gathering systems. 3. Develop new testing techniques and procedures. 4. Development of interpretation and analysis methods for hydraulic well testing and for temporary completion testing. 5. Development of methods of analysis of data from passive reservoir response.
II. Definition of Reservoir Characteristics	D. Geochemical Techniques and Problems	1. Summarize experience in the use of geochemical principles and techniques for exploitation applications including a data base and relate to need for work in "2" (below). 2. Investigations of basic geochemistry, including not only equilibrium situations but those having kinetic effects as well. 3. Application of geochemical techniques and principles.
III. Description of Example Reservoirs	A. Fundamental Studies of Geothermal Phenomena	None
III. Description of Example Reservoirs	B. Field Case Histories	1. Comprehensive documentation of specific sites. 2. Synthesis, generalization and development of conceptual models from field case histories. Note: Review Task Force recommended this task be a part of section "Fundamental Studies".

Table 1, cont'd.

IV. Modeling the Behavior of Geothermal Systems	A. Analytical Modeling	1. Formulation and analysis of the basic equations for mass and energy transport in geothermal systems.
		2. Analysis of short term well behavior. (Note the relationship of this project to the Research Category II-C, "Well Testing".)
		3. Problems in heat transfer.
		4. Problems in conduction and convection.
IV. Modeling the Behavior of Geothermal Systems	B. Numerical Modeling	1. Evaluation of existent codes.
		2. Evaluation of the basic phenomena governing reservoir behavior.
		3. Improvement of numerical models.
		4. Application to hypothetical but important production/reinjection exploitation schemes.
		5. Inverse problem.
		6. Improved numerical techniques.
IV. Modeling the Behavior of Geothermal Systems	C. Physical Modeling	1. Define more fully the theory of scale modeling for geothermal systems.
		2. Conduct experiments.
		3. Investigations of specific sites using physical modeling.
V. Exploitation Strategies	1. Exploitation Strategies	1. Review and assessment of existent strategies.
		2. Development of new and alternative strategies.
		3. Case studies.
VI. Economics	1. Economics	1. Assess existing economic evaluation methods from other mineral industries.
		2. Develop integrated life cycle economic model for geothermal resource development.
		3. Risk analysis as a part of integrated life cycle economic model.
		4. Comparative economics with alternate energy sources.

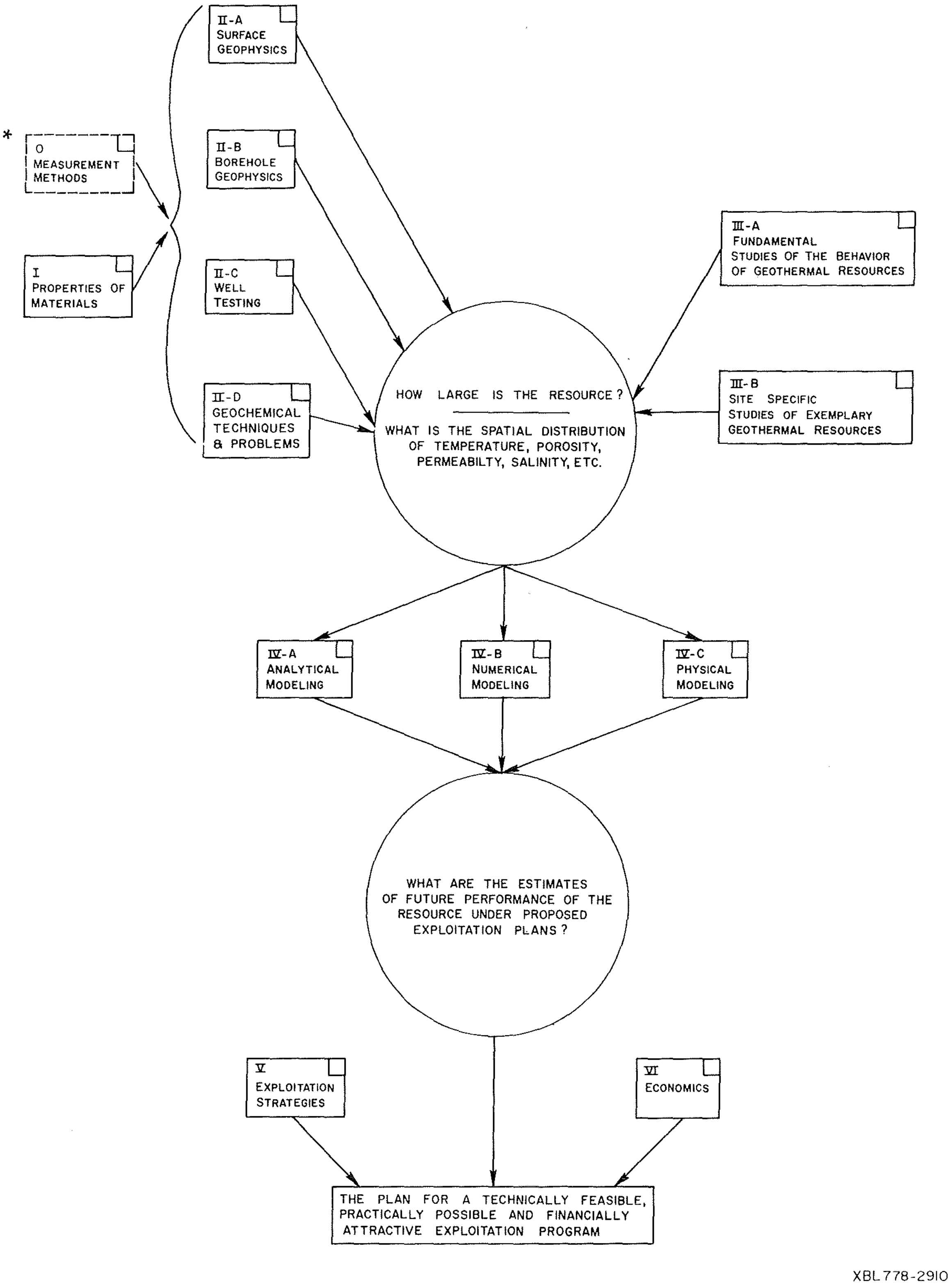

Figure 2. Overview of the Geothermal Reservoir Engineering Program.

*The element "Measurement Methods" is being handled outside GREMP at this time.

be accomplished by participating in the planning and review of the Geothermal Logging Development Program at Sandia, Albuquerque, and the Geothermal Log Interpretation Program at LASL. Participation will include soliciting their inputs for review of our plans for program implementation, periodic meetings and reports to their management staffs and review panels, and participation in their respective program planning and task force reviews.

RESEARCH ELEMENTS

PROPERTIES OF MATERIALS

Laboratory measurements of physical properties under conditions representative of geothermal reservoirs would be useful for interpreting geophysical field data and for modeling reservoir performance. Unfortunately, such measurements are either sparse or non-existent. Often, they must be generated by extrapolation or analogy, and the estimates yielded by these methods hardly suffice. If relevant data were available, geophysical measurements could be used more reliably to determine important information, such as the permeability and available porosity of the reservoir. Specifically, the data would assist in well-log interpretation, provide an interpretive framework for field surveys, and be useful in forecasting changes in the reservoir during exploitation. The specific measurements to be performed on typical reservoir rocks (as a function of temperature, pressure, pore pressure, and pore fluid composition) would include, though not be limited to, porosity, ultrasonic velocities, electrical conductivity, permeability, compressibility, thermal conductivity, heat capacity, and thermal expansion.

DEFINITION OF RESERVOIR CHARACTERISTICS

Surface Geophysics

Although surface geophysical techniques are widely used in geothermal exploration, less attention has been given to them as a tool for reservoir assessment. For the latter purpose, a surface geophysics program could help define the physical boundaries and characteristics of a reservoir and monitor the reservoir's behavior during production.

Several surface geophysical methods have been used, either singly or in combination, for reservoir assessment: active seismic, passive seismic, electrical and electromagnetic, gravity, and heat flow. These techniques and the instrumentation they employ need to be evaluated in terms of their ability to meet geothermal reservoir assessment capabilities; specific needs for improvements in instrumentation, data handling, and interpretation should be identified. Once this is done, recommendations for the advancement of these capabilities can be made, and their implementation carried out.

Interpretive Borehole Geophysics *

Well logging involves taking measurements, from a borehole, of the physical and/or chemical properties of rocks and the fluids of rock systems to analyze subsurface structure. The information obtained helps determine the location, size and potential production of a geothermal resource.

Because present understanding of geothermal reservoirs is limited, well logging instrumentation, techniques and interpretation are limited as well. The objectives of this research category are to: 1) assist, in a research context, in motivating private industry to increased efforts in geothermal exploration and development; 2) evaluate and select parameters to be logged, e.g., heat capacity; 3) develop instrumentation for geothermal well logging, as opposed to borrowing from the petroleum industry, to obtain better logging quality; 4) improve interpretation techniques by developing a geothermal well log data base, standardized calibration and normalization procedures, and dependable empirical/ statistical correlations.

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* LASL is responsible for the development and operation of calibration holes, the establishment and refinement of a logging data bank, and development of improved interpretation techniques.

Well Testing

Well testing helps determine the size and producibility of a resource, as well as evaluate the condition and flow capacity of the well. Geothermal well testing is more difficult and less perfected than the well testing techniques of hydrology and petroleum engineering. The geothermal well environment is often two-phase and non-isothermal, and methods have not yet been perfected for data interpretation in such conditions. Further, the geothermal environment is highly adverse to reliable data collection because it may have problems such as extremely high temperatures and corrosive brines. Thus, improvement of geothermal well testing techniques would have to include support for a more complete definition of testing conditions, development of instrumentation that can withstand hostile geothermal environments, development of new procedures for simultaneously evaluating mass- and heat-related properties, and improvement of interpretation and analysis techniques.

Geochemical Techniques and Problems

An improved understanding of all constituents of interest in geothermal resource exploitation must be undertaken if the capability of geochemical techniques is to be more fully understood and extended into more useful ways. The objectives of this research category are: 1) to determine the currently existing capability and applicability of geochemical principles, 2) to enhance this capability through improved understanding of the behavior of dissolved chemicals, noncondensable gases, and isotopes and through continued application for exploitation purposes, and 3) to understand and solve chemical problems associated with injection and production of fluids. More specifically, the achievement of these objectives would involve support for: synthesis of the experience to date in the use of geochemical techniques for exploitation application; investigations of the behavior of chemical species, dissolved gases, and isotopes under various production situations; studies of petrology and isotopes of reservoir rocks; additional applications to geothermal reservoirs of geochemical techniques currently believed to be well understood; incorporation of understanding of the behavior of reacting and non-reacting constituents into mass and energy transport codes; and still additional applications as understanding of the basic behavior of isotopes improves.

DESCRIPTION OF EXAMPLE RESERVOIRS

Fundamental Studies of Geothermal Phenomena

The behavior of geothermal reservoirs at their most fundamental level is the focus of this research category. Topics to be investigated might include, for example, the conceptualization of a geothermal resource, the heat source for particular geothermal reservoirs, physical properties that bear on the thermodynamic behavior of rocks and brines found in geothermal reservoirs, physical properties bearing on the fluid properties of brines. This is basic research that will yield a better scientific basis on which to develop a technology for the exploitation of geothermal reservoirs. A level of understanding comparable to that of the petroleum industry would be desirable.

Field Case Studies

A substantial amount of geological information about geothermal resources exists, but is not oriented to resource exploitation. Information useful for planning exploitation would best come from site specific studies of geothermal resources, rather than theoretical studies. Documentation of existing geothermal reservoirs would establish an "experience base" to give insight about future geothermal development. Opportunities for such documentation are available at many sites throughout the world; data from these sites could be collected, synthesized, and generalized to provide a new data base.

The documentation of specific sites would address the following features of prime interest to a developer: distributions of temperature, pressure, porosity, permeability, and chemical species; and energy and mass recharge systems.

MODELING THE BEHAVIOR OF GEOTHERMAL SYSTEMS

Analytical Modeling

Analytical modeling formalizes the understanding of the physical processes governing reservoirs, helps forecast reservoir performance, and contributes to the calibration of numerical models. However, much more remains to be done with analytical modeling in the geothermal industry. There is a need to first review the known mathematical formulations describing geothermal system behavior, i.e., the basic equations for mass and energy transport in porous, fractured media, and then to more clearly illuminate and analyze them. Simplification of the formulations should be applied to analytically tractable problems to discover whether they are of defensible value, and to determine how difficult it would be to solve fully rigorous formulations.

Numerical Modeling

Numerical modeling is the mathematical simulation of natural processes by incorporating physical and chemical principles into a mathematical framework. Various techniques are available for numerical modeling (e.g., finite difference methods, finite element methods, integrated finite difference methods) and complex problems involving a large number of variables can be handled. For example, a physics model might investigate two-phase and mass flow in a geothermal system; a chemical simulation might involve fluid and heat transfer reactions.

Much basic information is lacking for numerical modeling, so improvement in the understanding of physical and chemical phenomenology would be necessary before geothermal reservoir behavior could be meaningfully modeled. Further, the simulators that are currently used in modeling should be evaluated, and their limitations identified. Both modeling capability and numerical methods need to be improved. Breakthroughs are expected in the latter area, and more powerful numerical techniques are hoped for in the next generation of simulations.

Physical Modeling

Physical modeling is the use of scale or analogue models to illuminate patterns of mass and heat transfer in geothermal reservoirs. This kind of modeling gives the researcher a truly physical sense of the phenomena under investigation, yields real and continuous results, and may be used as a basis against which analytical and numerical results are compared. Also, physical models can possibly handle the mathematically intractable problems that bypass analytical and numerical modeling. To fully evaluate the usefulness of physical modeling, its theoretical basis must be elucidated from the point of view of geothermal resource exploitation, and the modeling should be applied to specific developed sites.

EXPLOITATION STRATEGIES

Because the development of a geothermal resource involves a complex of systems (e.g., well system, energy conversion system, disposal system), there are many possible strategies and options for exploitation. The problem for this research category is to identify the particularly effective strategies. To accomplish this task, reference has to be made to the exploitation strategies used by other mineral industries, to learn from their experience. Then, there is a need to determine what strategies have been used in presently developed geothermal sites, if these exist and can be reconstructed. Finally, these strategies need to be reviewed and analyzed to determine the method for optimum geothermal exploitation with respect to some stated criterion (e.g., maximum profit, minimum investment, maximum energy recovery, minimum disturbance to the environment).

ECONOMICS

Economics plays a critical role in geothermal development. Justification of geothermal exploration and exploitation programs depends upon the assessed economic value of a geothermal reservoir, based on the potential of the reservoir under a particular development strategy. The determination of the economic value is complex and involves consideration of the reservoir, the energy conversion technology, and the life cycle costing parameters. It also involves substantial risk as assessments must be made from limited data.

A methodology is not currently available for determining the level of economic risk associated with geothermal development. This research element proposes to assess the merits of existing economic evaluation methods and develop an improved economic assessment capability which combines reservoir mechanics and surface energy conversion technology into a single framework; and develop a capability to assess measurement accuracy, uncertainties in data interpretation, and reservoir performance as related to decreasing development risk.

IMPLEMENTATION OF GREMP

Upon completion of the plan and schedules for GREMP, implementation of the program will begin with announcements, to be placed in the Commerce Business Daily (CBD), of LBL's intent to issue Requests for Proposals (RFP's). The RFP's will then be available shortly after the CBD announcement. The three top priority research categories identified by the Review Task Force will be the subjects of the first RFP's. The LBL RFP's will be sent to all respondents to the CBD announcements who are deemed qualified as well as other organizations which are known to LBL and are qualified. Proposals from any qualified organization will be considered.

PREPARATION OF RFP'S

RFP's will be drafted that contain a statement of the research problem and the scope of work to be undertaken based on the category descriptions in Appendix A and incorporating the recommendations of the Review Task Force. The foregoing will be prepared by the Technical Support Team and will be reviewed by the Administrative Support Team. The LBL Purchasing Department will then prepare the completed RFP for each research category. These complete RFP's will contain the following items.

1. Statement of the problem.
2. Scope of work by tasks.
3. Suggested milestones for the contract.
4. Manpower/level-of-effort expected to achieve the scope of work.
5. Schedule of reporting dates, reviews, travel, etc.

6. Duration of contract, with extension options, if any.
7. Request for proposals regarding additional optional tasks which the proposer deems essential to the understanding of the problem or to advance the state of the art.
8. A request for detailed cost estimates by task, to cover items 2-5 above to include all labor, burdens, other direct costs, and fee information in DD633 format. If additional optional tasks are proposed (item 7) separate cost estimates for this work will be requested.
9. A request for separately bound and sealed technical proposals and management (cost) proposals to allow for independent technical evaluation by the Proposal Evaluation Committee without including any cost data.
10. A statement describing the acceptability of various research contractors such as single organizations, cooperative efforts, joint ventures, use of consultants, prime/sub-contract arrangements, etc.
11. A statement relating to the acceptability of responses to part of the statement of work whether optional tasks are included or not.
12. A statement indicating that a firm fixed price, level of effort proposal is the desired type, although under specific circumstances to be determined, other proposal types such as cost plus fixed fee, time and materials, cost plus no fee, etc., may be accepted.

13. Evaluation criteria by order of importance to be used by the proposal evaluation committee.
14. LBL Standard Contractual Terms and Conditions.

Competitive bidding is normally required by both DOE and LBL regulation and policies. However in those cases where it is impractical to place a specific requirement on a competitive basis, the DOE/LBL procurement system will allow non-competitive procurement on a sole-source basis.

SCHEDULE FOR RFP ACTIVITIES

An approximate time table for RFP's, evaluation of proposals and awarding of contracts is outlined below and shown in Fig. 3.

	Action	Schedule
1.	Announcement in CBD	Based on priorities and GREMP plan
2.	Issue RFP	Based on CBD announcements
3.	Receipt of proposals	45 days from issuance of RFP
4.	Review & selection by Evaluation Committees	15 workdays from due date of proposals
5.	Concurrence with selection by DOE	5 workdays
6.	Completion of contract negotiation	10 workdays
7.	Execution of contract	10-15 days after negotiation completion

EVALUATION OF PROPOSALS

A Proposal Evaluation Committee will be commissioned at LBL to include LBL technical and administrative personnel, technical personnel from academic institutions, and consultants as needed. The LBL GREMP project manager will act as chairman. In its evaluation of proposals,

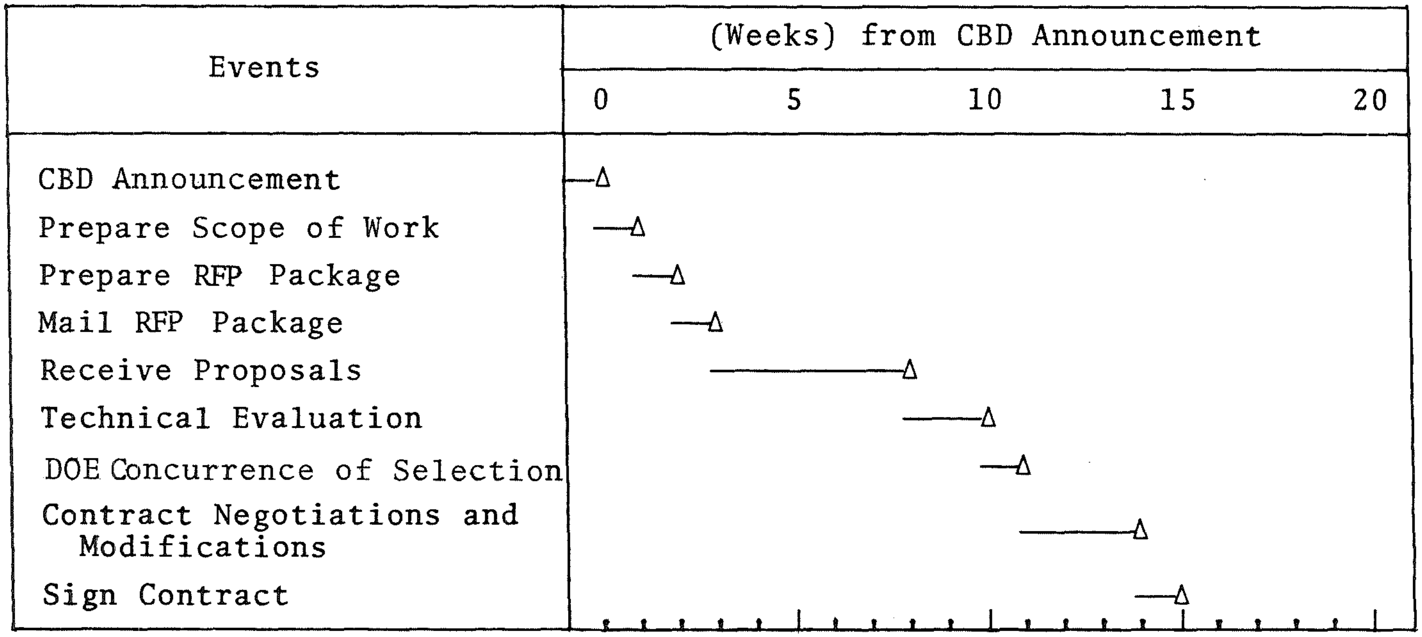

Figure 3. The competitive procurement planning schedule for GREMP.

the committee may ask for additional materials either in written form or as verbal briefing, if it would contribute to the evaluation.

The evaluation and selection of contractors will be done in two steps as follows:

1. The best technical proposals will be selected without referral to the accompanying sealed cost management proposals. Special weight factors designed for this technical selection will be used.
2. Cost management proposals will be selected on a weighted basis derived from the technical proposal selections made in the first step.

In certain procurements a one step weighted evaluation and selection procedure will be used to include both technical and cost proposals.

CONTRACT NEGOTIATION

Upon concurrence with the Proposal Evaluation Committee's selections by DOE/DGE and the LBL Technical and Administrative Teams, negotiations will be initiated with the contractor judged to be most qualified from a technical and cost point of view.

Any modifications of the scope of work, changes in schedule or "best and final offers" solicited from the selected potential contractor will also be requested from the other organizations deemed acceptable.

If negotiations with the top rated organization cannot resolve the differences, they will be so informed and negotiations will be started immediately with the next selected organization.

CONTRACT PREPARATION

During contract preparation, the Technical Team members will take the lead in preparation of the scope of work, deliverable items and all items related to technical requirements. In addition, insofar as they affect the legal and business aspects of the contract, the technical support team will work with the administrative team in developing an integrated approach to a contract with the desired scientific and technical level of effort that is legally sufficient and within the available funds.

The mission of the Legal Advisor will be to ensure that legal, patent, and data requirements are developed within the legal requirements of the procurement procedures.

This function includes monitoring the reports from any R&D contract effort administered by LBL. LBL will follow the DOE patent policy and will use DOE approved standard patent provisions to insert in contracts. Should questions arise or waivers be requested, LBL will call on the San Francisco Operations Office (DOE) Patent Group for assistance.

Financial administration responsibility includes the adequacy of the contractor's accounting system, and reasonableness and accuracy of the cost estimate. It will be the responsibility of the Administrative Team member to analyze audit comments and other available data so that he can adequately advise the Project Manager on a monthly basis.

With the advice and assistance of all the other team members, the Procurement Specialist will be responsible for the overall contract document that will be forwarded to the contractor for acceptance.

MANAGEMENT OF RESEARCH CONTRACTS

Once a contract has been signed, LBL will exercise a continuing technical and financial overview of contractor performance to ensure compliance with the terms and conditions of the agreement. This overview will consist of site visits, meetings, and review of written financial and technical reports.

During the duration of the contracts LBL and its consultants will continuously assess the technical progress and make appropriate revisions to the contracts necessary. Since these revisions may involve a change in reporting dates and/or costs, such changes will be formalized through the Contract Administrator to ensure that any modifications of an existing contract meets all LBL and DOE terms and conditions as well as the approval of the contractor's team.

At regular intervals of at least once a year, and at prearranged milestones of the contractors, the status of GREMP will be reviewed to recapitulate the progress obtained from its active programs and other sources. These reviews will include: transfer of technology to appropriate agencies and industries through workshops, seminars, symposiums, technical presentations, technical papers and reports, and meetings with DOE/DGE. In addition, LBL will ensure that all pertinent information from the research contracts are presented in a format compatible with an informal data storage and retrieval system utilizing the National Geothermal Information Resource (GRID) system.

REVIEW OF THE GREMP PLAN

Starting with the issuance of the GREMP Plan and until the successful completion of the GREMP, the Plan will be continually revised and updated in the light of new developments in the geothermal reservoir engineering field in general and as a result of the data obtained from GREMP research contracts in particular.

RESEARCH SCHEDULE

In accordance with the recommendations of the Review Task Force, LBL plans to issue RFP's involving the following GREMP research categories early in FY-1978. They are listed in order of priority.*

1. Well Testing
2. Geochemical Techniques and Problems
3. Properties of Materials

RFP's involving other research categories will be issued later in FY-1978 and in FY-1979 contingent on funding levels, the availability of results from on-going research, and later recommendations of the Review Task Force during these fiscal years as the program progresses.

Figure 4 is a GREMP schedule that incorporates the priorities and contingent factors outlined above.

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*Note that the second highest priority category was actually Interpretive Borehole Geophysics (II B). However, inasmuch as this category is now being finalized and implemented at LASL, it is not listed among the top three categories for which LBL has responsibility.

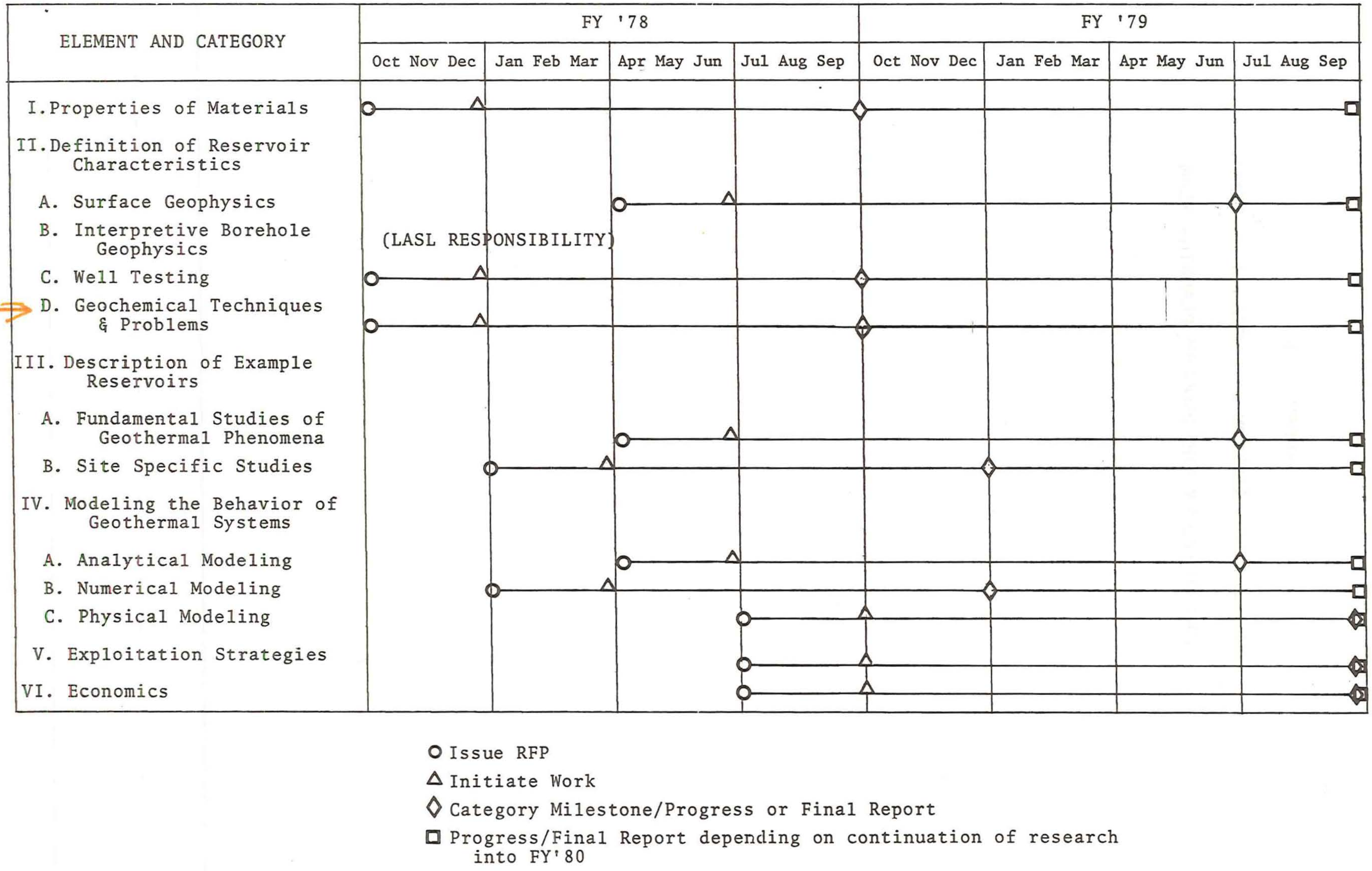

Figure 4. GREMP research schedule. The three research categories beginning in October of FY-78 are first priority projects, in accordance with the recommendations of the Review Task Force (see section on Research Schedule).

APPENDIX A

DETAILED DESCRIPTION OF RESEARCH ELEMENTS IDENTIFIED BY THE PROGRAM PLANNING TEAM

ELEMENT I: PROPERTIES OF MATERIALS

Background

In order to interpret the data obtained from field geophysics measurements as well as well-logging tools which exist or may be developed for geothermal wells, laboratory data under relevant conditions must be available. Since the conditions of the laboratory measurement must closely simulate the reservoir environment, parameters which should be considered independent variables in relevant experiments include, but may not be limited to, rock type, porosity, structural state (cementation, fracturing, etc.), temperature, confining pressure, pore pressure, and pore-saturant chemistry. Correct interpretation of field data should provide information on the heat and the fluid conductivity and the capacity of the reservoir. The ideal situation would be one which leads ultimately to spatial resolution of these properties in three dimensions.

Laboratory measurement of physical properties at the relevant conditions for a given reservoir should allow interpretation of routine and specialized field measurements. In order for these experiments to be useful, however, samples must be carefully characterized as to pore structure, chemistry and phase relationships before and after laboratory experiments are performed. Most meaningful physical property measurements need to be supported by petrographic studies involving optical and scanning electron microscopy, chemical characterization by the electron microprobe, and definition of pore structure.

Statement of the Problem

Laboratory measurements of physical properties at conditions relevant to most geothermal reservoirs are either sparse or non-existent at present. The situation for electrical properties typifies the problem. A recent workshop on geothermal exploration (Ward et al., 1977) concluded: "Most strongly endorsed was a need for comprehensive, high quality, laboratory studies of the electrical properties of rocks under temperatures, pressures, and solution chemistries pertinent to the geothermal environment. Unless we can move off square one in this basic area, the very foundations of electrical methods are in question."

Some data do exist and are useful to gain "first cut" answers to questions concerning permeability, heat capacity, thermal diffusivity, and porosity. A good recent summary of the petroleum literature on these topics which seeks to apply them to the geothermal problem is that of Ramey et al. (1974). However, very few of the results summarized can be applied directly to a particular geothermal system. No complete data set in which pressure, temperature, and pore fluid composition and pressure are varied is available. One has to rely on extrapolation and analogy to get an estimate of the value of a parameter in a geothermal log. Also, when large expenditures of time and dollars depend on the proper interpretation of such logs, extrapolation and analogy will not suffice. The work of Aruna et al. (1977) demonstrates that extrapolation is not a reliable predictor of physical properties. They found a large reversible decrease in permeability of sandstone to water in the temperature range 21°-150°C which is attributed to "...unsuspected fluid-solid surface attractive forces between water and quartz..." (our emphasis).

Somerton et al. (1974) have measured V_p, V_s and compressibility to about 100 MPa and 200°C on sandstones and siltstones, some of which were saturated with a KCl brine. In addition, they also determined the thermal conductivity at 133°C and 3 MPa confining pressure on some of these rocks. Electrical conductivity to 200°C and an effective stress of about 7 MPa has been measured on shaly sandstones as a function of brine composition (Waxman and Thomas, 1972).

However, these studies have limited application to geothermal well-log and field survey interpretations. The paramount shortcoming is that the rock types studied have been limited to petroleum reservoir rocks. Igneous and metamorphic rocks have been studied over a much more limited range of pressure-temperature-saturant chemistry (see, for example, Spencer and Nur, 1976; Brace et al., 1965, 1968; Duba et al., 1974). Another shortcoming is the lack of simultaneous measurement of several physical properties on the same core. Cycling the sample in laboratory experiments produces changes in crack structure (Simmons et al., 1974) so that sequential information is unreliable for correlating changes in different physical properties when stress or temperature is cycled. Correlations based on simultaneous measurements are essential if information on the permeability, porosity, or salinity of a geothermal reservoir is to be inferred from sonic and resistivity logs.

Discussion of the Solution

Laboratory data on the variation of the physical properties of reservoir constituents as a function of pressure, temperature, and saturant salinity would be invaluable in the interpretation of field measurements, and modeling of reservoir performance. If such data were available, we would be able to interpret geophysical data in terms of parameters the reservoir engineer needs to know--the permeability and available porosity of the reservoir. In addition, these data could be useful for designing and interpreting monitoring tools to detect changes in reservoir properties during production. This information would be vital if reservoir stimulation schemes are evolved and employed in geothermal systems.

Specific measurements to be performed include, but should not be limited to:

1. porosity,
2. permeability,
3. ultrasonic velocities,
4. electrical conductivity,
5. compressibility,
6. thermal conductivity,
7. heat capacity, and
8. thermal expansion.

on typical reservoir rocks as a function of temperature, pressure, pore pressure, structural state of the rock, and pore fluid composition. Simultaneous measurement of several properties and measurements spanning various durations would be encouraged. Support should be sufficient to provide adequate characterization of the mineral samples pre- and post-experiment with respect to porosity, chemistry, mineralogy, and pore structure.

Project Objectives

Project objectives are:

1. to assist in well-log interpretation,
2. to provide interpretative framework for field surveys, and
3. to determine changes in the reservoir during exploitation.

Somerton et al. (1974) have measured V_p, V_s and compressibility to about 100 MPa and 200°C on sandstones and siltstones, some of which were saturated with a KCl brine. In addition, they also determined the thermal conductivity at 133°C and 3 MPa confining pressure on some of these rocks. Electrical conductivity to 200°C and an effective stress of about 7 MPa has been measured on shaly sandstones as a function of brine composition (Waxman and Thomas, 1972).

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Project Objectives

Project objectives are:

1. to assist in well-log interpretation,
2. to provide interpretative framework for field surveys, and
3. to determine changes in the reservoir during exploitation.

These objectives will be met only if reliable well-log and survey data are available and if laboratory studies supported under this project are successful in providing the basis for meaningful determination of the response of geothermal rocks to environmental variables.

Discussion of Research Projects

The research projects in Table I-1 are not meant to be exhaustive. These particular projects would aid in meeting the objectives discussed above. The importance of simultaneous measurements and investigation of rocks relevant to geothermal systems cannot be stressed too much. Adequate sample characterization both pre- and post-experiment should be a requirement. Characterization should include optical and electron microscopic studies, phase identification, and chemical characterization of phases. For a significant rate of progress, the budget for these projects should include about $300 K for equipment and should be capable of supporting 6-10 scientists per year.

Research Schedule and Anticipated Results

Table I-2 also includes the proposed schedule for research in this vital area. This schedule is meant to be flexible, but items should not be allowed to slip for too long because of the long lead time between funding of an experimental project and the production of useful results. Some capital expenditure will be necessary for the accomplishment of the objectives detailed above. If these objectives are to be achieved, the laboratory experiments should be funded in as timely a manner as possible.

Interfaces

This project will provide an interpretative basis for both the borehole and surface geophysics projects. Data collected from new methods of measurments will also be interpreted in light of the results obtained by this project. Well testing will also rely on laboratory permeability measurements made on reservoir rocks to correlate and calibrate field techniques. Reservoir performance modeling studies will also depend on data and models derived from this project.

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TABLE I-1

RESEARCH PROJECTS FOR PROPERTIES OF MATERIALS

RESEARCH CATEGORY	RESEARCH PROJECTS	RESEARCH TASKS
Properties of Materials	1. Simultaneous measurement of electrical conductivity, acoustic velocity, compressibility, thermal expansion, porosity, permeability, and the effects of fractures on permeability, porosity, etc. in rocks saturated with saline solutions at elevated temperatures, various pore pressures, and differential stress status.	a. Igneous rock b. Metamorphic and sedimentary rocks c. Geothermal reservoir rocks using geothermal fluids
	2. Simultaneous measurement of thermal conductivity and heat capacity in rocks saturated with saline solutions at elevated temperature and pressure.	a. Igneous rock b. Metamorphic and sedimentary rocks c. Geothermal reservoir rocks using geothermal brines
	3. Effect of solutes at saturated values on long-term behavior of physical properties of rocks at elevated pressure and temperature.	
	4. New techniques for:	a. Thermal property measurement under chemical and physical conditions relevant to geothermal systems. b. Compressibility and thermal expansion measurement at physical and chemical conditions relevant to geothermal systems.

TABLE I-2

RESEARCH PROJECT	FY '78													FY '79												
	O	N	D	J	F	M	A	M	J	J	A	S	.	O	N	D	J	F	M	A	M	J	J	A	S	.
1. Electrical acoustic and thermal expansion properties vs. porosity, permeability and compressibility, etc.																										
a. For igneous rocks	○	—	—	—	—	—	—	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	—	□
b. For metamorphic and sedimentary rocks	○	—	—	—	—	—	—	—	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	—	□
c. For geothermal reservoir rocks													○	—	—	—	—	—	—	—	—	—	—	—	—	△
2. Thermal conductivity and heat capacity.																										
a. For igneous rocks													○	—	—	—	—	—	—	—	—	—	—	—	—	□
b. For metamorphic and sedimentary rocks	○	—	—	—	—	—	—	—	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	—	□
c. For geothermal reservoir rocks													○	—	—	—	—	—	—	—	—	—	—	—	—	□
3. Long-term behavior of solutes at saturation levels.													○	—	—	—	—	—	—	—	—	—	—	—	—	□
4. New techniques																										
a. Thermal properties													○	—	—	—	—	—	—	—	—	—	—	—	—	□
b. Compressibility and thermal expansion.													○	—	—	—	—	—	—	—	—	—	—	—	—	□

Legend:

○——— Proposed start of project/task.

□——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———□ Indefinite milestone.

ELEMENT II: DEFINITION OF RESERVOIR CHARACTERISTICS

CATEGORY A: SURFACE GEOPHYSICS

Background

While surface geophysical techniques are widely used in geothermal exploration, there has been less attention given to surface geophysics for reservoir assessment. This situation is due in part to the youthfulness of the geothermal industry, which is in a period of intensive exploration and which has few producing fields. If the industry follows a normal evolution similar to other resource development industries, there will be a growing need to devise new techniques or adapt existing surface geophysical techniques for reservoir assessment. The objective during exploration is to locate targets for confirmatory drilling. If this phase is successful and a geothermal reservoir is established, the objectives of a surface geophysics program during the assessment, development, and production phases would be:

(1) To define the physical boundaries and characteristics of the reservoir, and

(2) To monitor reservoir behavior during production.

Geophysical research as it relates to reservoir assessment and engineering is addressed in this research planning element. Research designed to accomplish the objectives of defining the physical boundaries and monitoring the reservoir are described in detail in this planning document.

Reservoir assessment deals, in part, with evaluating the geometry and physical parameters (e.g. temperature distribution, salinity, porosity, permeability, etc.) of the reservoir. As new reservoirs are developed and existing reservoirs are expanded it is expected that surface geophysical assessment work will be increasingly better documented by case history examples, and there will be a need to improve existing techniques or develop new techniques for this purpose. Several surface geophysical methods have been used singly or in combinations for reservoir assessment including:

1. Active seismic
2. Passive seismic
3. Electrical and electromagnetic, including both active and passive modes of signal generation
4. Gravity
5. Heat flow.

A brief background discussion concerning these methods follows.

Active Seismic

High resolution reflection and refraction methods have been applied at only a few geothermal reservoir areas. These techniques are potentially powerful tools for identifying and inferring structural or stratigraphic features, such as faults or densified cap rocks. These features tend to define the boundaries of a reservoir. Bright-spot reflection analysis may also assist in defining vapor-saturated portions of a reservoir.

Passive Seismic

Promising passive seismic techniques for estimating the extent of a reservoir involve investigation of P and S wave velocities and amplitude attenuations as revealed from local and distant earthquakes or man-made sources. At both Coso Hot Springs (Combs and Rotstein, 1975) and at The Geysers (Majer and McEvilly, 1977) P and S velocities gave anomalously low Poisson's ratios which correlate with a known or suspected reservoir area. The effect is believed due to a vapor phase within the reservoir.

Electrical and Electromagnetic

Electrical and electromagnetic techniques provide information on reservoir boundaries if a resistivity contrast exists between reservoir and non-reservoir rocks. Early experience at fields in New Zealand indicated that dc electrical resistivity measurements (Risk, Macdonald and Dawson, 1970) and audio-frequency magnetotellurics (AMT) (Whiteford, 1975) could be used to map the field boundaries. These methods proved useful because the fields are characterized by resistivity contrasts that are not only significant, but occur at or close to the surface. Elsewhere, these methods have been less diagnostic and harder to apply and interpret because of greater depth to the reservoir or less resistivity contrast. It was noted by Swanberg (1975), for example, that electrical and EM techniques would be difficult to apply in the Imperial Valley where the normal ground water may have a high salinity and corresponding high conductivity. Vapor-dominated systems, such as The Geysers, have reservoir regions that are likely to have higher intrinsic resistivity than the surrounding rocks.

The induced polarization or IP method may have some use for reservoir delineation. The IP method was able to identify a polarizable pyritic zone at West Yellowstone, which occurs due to mixing between rising sulfur-rich thermal waters and meteoric waters (Zohdy, et al, 1973). An IP effect, due possibly to clay minerals, was also noted near the boundary of the Broadlands, N. Z. field (Risk, 1975).

Gravity

A close association is reported between several known or potential geothermal reservoirs and gravity anomalies. Interpretation of the anomalies suggest that these data might provide useful information on the lateral extent of the reservoir region. Gravity highs occur for a variety of reasons, some of which may have a direct correlation with the reservoir geometry; e.g. young silicic intrusives, faulting, and densification of the thermally affected zone, either by hydrothermal metamorphism or by precipitation of secondary minerals in fractures and pores. In this reagrd, there is evidence in the Imperial Valley and at Cerro Prieto, Baja California that good correlations exist between the fields and gravity anomalies.

In addition to reservoir delineation, attempts are being made to use high precision gravity measurements, coupled with second-order levelling, to separate subsurface changes from subsidence effects at a producing field. Repeated measurements at The Geysers (Isherwood, 1977) and at Wairakei (Hunt, 1970) show that reductions in gravity occur which can be used to estimate the net mass loss and to indicate the area from which fluids have been withdrawn and not replenished by recharge.

Heat Flow

Closely-spaced shallow heat flow holes may provide, under ideal circumstances, one of the best and most direct means for delineating the lateral boundaries of a reservoir. However, where hydrothermal connection occurs, upon which the effects of near-surface hydrology may be superimposed, the heat flow picture at the surface could become distorted and no longer give a reliable picture of the subsurface reservoir geometry.

Statement of the Problem

Existing surface geophysical techniques and the instruments employed therein need to be evaluated in terms of their effectiveness to meet reservoir assessment and monitoring objectives. Undoubtedly these techniques and instruments will have to be improved, and perhaps a need for new techniques and instrumentation can also be documented. An effort in evaluation of techniques and instruments clearly needs to be undertaken. So far as technique evaluation is concerned, it is imperative that such evaluation be conducted at sites having adequate subsurface control on the reservoir.

Discussion of the Solution

Available surface geophysical instrumentation and techniques need to be assessed so that specific needs for improvements in instrumentation, data handling, and interpretation can be identified. Once these needs are identified, development of new methods of data handling and interpretation can proceed and instruments can be improved or developed for greater utility, as appropriate.

Research Objectives

The objectives of this category of the program include:

- Evaluation of existent capability of instrumentation, data gathering systems, and methods of analysis bearing on the problems of reservoir assessment and monitoring.
- Recommendation for advancement of these capabilities.
- Implementation of the recommendations.

Research Program

Opportunities for research exist in all areas of geophysics that are identified by the geophysical technique itself. Included are the following techniques:

- gravity
- active seismic methods
- passive seismic methods
- electrical and electromagnetic methods
- heat flow analysis

For each of these there is a need for evaluation of existent capability -- including instrumentation capability as well as capabilities to gather and analyze data so generated -- with emphasis on documentation of successful applications to date. Reports are called for explaining:

- the capability of available instruments
- the potential for upgrading available instruments
- the state of the art in analysis of data so acquired
- an assessment of apparent opportunities for upgrading analytical techniques.

In addition, the program element calls for support of new surface geophysics techniques, should there be any, for defining geothermal reservoirs for exploitation purposes. (An example is the possible extension of the "bright-spot" technique used in the petroleum industry.) It also calls for support of methods of combining various geophysical methods to enhance the usefulness of each and for review of strategies in their optimal application. (See also section on Exploitation Strategies.)

Clearly, following a phase of evaluation, there should be an effort to improve existent capabilities in ways guided by experience to date.

Table II-A-1 lays out these parts of the program element.

Research Schedule

The proposed schedule is shown in Table II-A-2. Early activity in connection with this program element is concerned with more clearly evaluating existing capabilities, but some support should be given also to new techniques and to new methods of combined applications of geophysical methods.

Interfaces

Geophysical research for exploitation purposes relates to reservoir engineering in particular in defining the external surfaces of a resource, to some extent its internal properties, and thus in setting up the geometry and internal conditions to model and forecast future performances. In turn, therefore, geophysics provides basic input to economic studies. Special note should be made of the ongoing geophysical research being carried out at the University of Utah Research Center (UURC). The institution has important programs that interface in a significant way with the reservoir engineering program.

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TABLE II-A-1

RESEARCH CATEGORY	RESEARCH PROJECTS	RESEARCH TASKS
Surface Geophysics	1. Evaluation of existent techniques	
	- gravity	a. Define capability for measurement of available instruments
		b. Evaluate need for improved capability
		c. Assess potential for upgrading available instruments, if appropriate; note bore-to-bore, bore-to-surface possibilities.
		d. Evaluate state of the art of analysis of data so acquired.
		e. Assess prospects for improved analytical techniques.
	2. - active seismic methods	As in above.
	3. - passive seismic methods	As in above.
	4. - electrical and electromagnetic techniques	As in above.
	5. - heat flow	As in above.
	6. Support for new geophysical techniques.	As in above.
	7. Review of combinations of geophysical techniques.	a. Combination of heat flow, and gravity techniques.
		b. Other combinations.
		c. Review of strategies for optimal combination of geophysical methods for exploitation purposes.
	8. Research into improved geophysical methods for exploitation purposes.	

TABLE II-A-2

RESEARCH PROJECT		FY '78													FY '79												
	.	O	N	D	J	F	M	A	M	J	J	A	S	.	O	N	D	J	F	M	A	M	J	J	A	S	.
1. Evaluation - gravity								○	—	—	—	—	—	△													
2. Evaluation - active seismic								○	—	—	—	—	—	△													
3. Evaluation - passive seismic								○	—	—	—	—	—	△													
4. Evaluation - electrical and electromagnetic								○	—	—	—	—	—	△													
5. Evaluation - heat flow analysis								○	—	—	—	—	—	△													
6. New techniques								○	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	—	□
7. Combination of techniques								○	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	—	□
8. Research on improvements in various geophysical methods														○	—	—	—	—	—	—	—	—	—	—	—	—	△(?)

Legend:

○——— Proposed start of project/task.

□——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———□ Indefinite milestone.

ELEMENT II: DEFINITION OF RESERVOIR CHARACTERISTICS

CATEGORY B: INTERPRETIVE BOREHOLE GEOPHYSICS

Background

Well logging involves measurement of physical and/or chemical properties of rocks and the fluids contained therein in a borehole. Such measurements, when related to parameters of ultimate interest, such as porosity, are useful in:

1. Exploration
2. Reservoir assessment
3. Reservoir development and management
4. Environmental, legal and institutional problems.

Well logging is indispensable for determining reservoir rock and fluid properties in order to assess the size and potential producibility of a geothermal resource. Well logs may also provide important information for decisions regarding location of wells as the field is developed and for decisions about drilling and completion techniques. Well logging also provides important information required for quantitative reservoir modeling and may provide valuable data bearing on environmental, legal, and institutional problems, such as inadvertent thermal and chemical pollution of potable groundwater.

Statement of the Problem

Problems in geothermal well logging research can be divided into the following categories:

- Economic and institutional problems.
- Selection of parameters to be logged and to be ultimately derived.
- Data gathering.
- Data interpretation.

Research on economic and institutional problems are not within the scope of the Reservoir Engineering Management Planning Program. However, it is important to realize that lack of financial incentives and concern over proprietary and patent rights have in some instances kept companies with established capabilities from participating fully in geothermal development.

Prior to logging a well, one needs to identify those parameters for which quantitative estimates are sought. This choice depends on the basic purpose (explorations, developments, etc.), resource type (e.g., liquid vs. vapor dominated), stage of exploitation of the field (e.g., are porosities already fairly well known?), and on operational and economic considerations (e.g., is the risk and expense of obtaining the data greater than the value of the data itself?). Present understanding of geothermal reservoirs is limited. Additional studies and reviews of geothermal reservoir performance will be needed before the parameter selection procedure for geothermal industry, much less for a given geologic province, is standardized.

An important problem facing the geothermal industry is the availability of instrumentation suitable for data gathering. The hardware currently used for geothermal logging is borrowed in toto from the petroleum industry, where well temperatures higher than 300°F are unusual. In geothermal reservoirs, temperatures can range up to 700°F. Most of the logging tools, cables and seals are rated to 350°F only. 500°F rated cables and seals are available; however, logging tools with temperature ratings above 350°F have sharply reduced efficiency and life expectancy when placed in the "hostile" environment of a geothermal borehole. (The problems of frequent breakdowns and loss of tools in the hole increase almost exponentially as temperatures increase above 350°F.) Since the life of a tool in these conditions is very limited, geothermal logging tools are rarely tested and calibrated under the extreme conditions to which they will be deployed. Logging of geothermal wells is an activity that is often rushed because of costly rig time and especially because of the desire to minimize the time of exposure of the tools to the hazards of a geothermal environment. Rushing leads to poor log quality and the tendency toward rushing could be reduced if tools adequately rugged to tolerate geothermal environments could be developed.

Geothermal reservoirs commonly occur in fractured igneous or metamorphic rocks, whereas petroleum reservoirs usually occur in sedimentary rocks having mainly inter-granular porosity and permeability. The lithology and pore structure of geothermal reservoirs are generally unfamiliar to the well logging industry. As a result, a satisfactory well log response data base does not exist. Also, standardized calibration and normalization procedures as well as adequately documented log interpretation techniques are yet to be developed for the geothermal industry. Dependable statistical and empirical correlations developed by and appropriate to the petroleum industry are simply not available to the analyst in the geothermal industry. Poor log quality, complex and unfamiliar lithology, lack of complete understanding of temperature and salinity effects on log responses, lack of a comprehensive data base, lack of dependable empirical/statistical correlations, and lack of standardized calibration and normalization procedures make geothermal well log interpretation a procedure ripe for improvement.

Discussion of the Solution

Solutions to the problems and research challenges stated above include:

1. Development of economic incentives and resolution of institutional impediments.

2. Review and selection of well logging parameters.
3. Development of new instrumentation for acquiring "downhole" data.
4. Thoughtful and constructive evaluation and improvement of techniques for interpretation.

This program element focuses on items 2 and 4, and the ongoing program at Sandia Laboratories, Albuquerque (SLA) and at Los Alamos Scientific Laboratory (LASL) focus on items 3 and 4.*

Project Objectives

Project objectives include:

- Assist, in a research context, in improving the economic and institutional basis for motivating private industry to participate in geothermal exploration and development.
- Evaluate more definitively the parameters of value and interest that can be obtained from well logging.
- Assist in the development of instrumentation capable of reliable operation at elevated temperatures in hostile geothermal environments.
- Promote the development of methods for standardized calibration and normalization of instrumentation and logging procedures to increase the reliability of well logging.
- Perform lab experiments.
- Promote the perfection and dependability of interpretative procedures.
- Promote development of new interpretation technologies and theoretical/empirical/statistical correlations.
- Promote development of a data base.
- Disseminate the research derived from these activities.

Discussion of Research Projects

The projects currently conceived under this category of research are listed in Table II-B-1. Although more detail could be given regarding each of these projects, the expectation is that the detail given is adequate to

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*Since the inception of GREMP, in fact the principal responsibility for the element "Interpretive Borehole Geophysics" has been transferred to LASL; instrumentation has been more completely and clearly assigned to SLA.

formulate request for proposal statements, to anticipate responses to each of the suggested projects, and to lay out a schedule for implementation of this category of the program.

Several comments are appropriate, however. First, it should be noted that for purposes of program implementation several of these projects could be grouped into single major projects, as appropriate. Second, "1) Economic and institutional framework" and the project "3) Improve and ruggedize logging tools" will be handled by other groups. Third, although calibration wells have been discussed as a means to evaluate and normalize log response, the possible use of calibration pits is not excluded. Fourth, two projects are recognized as so generally defined within this program document that work on the projects should be viewed on a level of effort basis only. These projects are "5) conduct laboratory experiments," and "7) develop interpretive technique". The overriding research nature of these projects is such that first and second year goals for instance are not possible to lay out (in contrast to the project "6) establish a data bank" for which a schedulable goal can be defined).

Research Schedule and Results

The proposed schedule for implementation of this category of research is shown in Table II-B-2. The schedule calls for completion of the following research projects by the third quarter of FY78: 1) definition of the parameters of value and interest in interpretive borehole geophysics, 2) establishment of criteria for selection of calibration wells, and 3) the evaluation of existent interpretive techniques. Other milestones in the implementation of the research category are as indicated in Table II-B-1.

Anticipated results of the research effort for the first two years are as follows. For the first year, there should be:

a. A definitive statement of the parameters desired as output from borehole geophysical methods and their relative priorities.

b. The establishment of criteria for the selection of calibration holes (and pits if that should prove to be a reasonable alternative or supplement).

c. Purchase of one or more calibration holes as funds and the availability of purchasable holes allows.

d. Laboratory research results describing the empirical relation between parameters of first order value and interest and other selected physical properties of rocks that could be measured in boreholes. (This activity is recognized as a level of effort activity.)

e. Establishment of a data bank of geothermal borehole information.

f. Evaluation of existent interpretive techniques.

For the second year there should be:

a. The purchase of calibration holes (if such had not been purchased during the first year).

b. Construction of calibration holes (and pits if appropriate) to satisfy, along with purchased holes, the needs of the overall program.

c. Laboratory research results describing the empirical relation between parameters of first and second order value and interest and selected other physical properties of rocks that could be measured in boreholes (level of effort program).

d. Expansion and refinement of the data bank.

e. The development of new interpretive techniques. (This activity is recognized as a level of effort activity.)

Interfaces

Attention should be called to the fact that two projects listed under this research category will be carried under the supervision of other groups. In particular, consideration of the economic and institutional framework within which borehole geophysics operates should be referred to the DOE/DGE branch of Institutional Studies. Furthermore, the improvement and ruggedization of logging tools is being conducted under the supervision of Sandia Laboratories, Albuquerque.

LASL is responsible for the development and operation of calibration holes, for the establishment and refinement of a logging data bank, and development of improved interpretation techniques.

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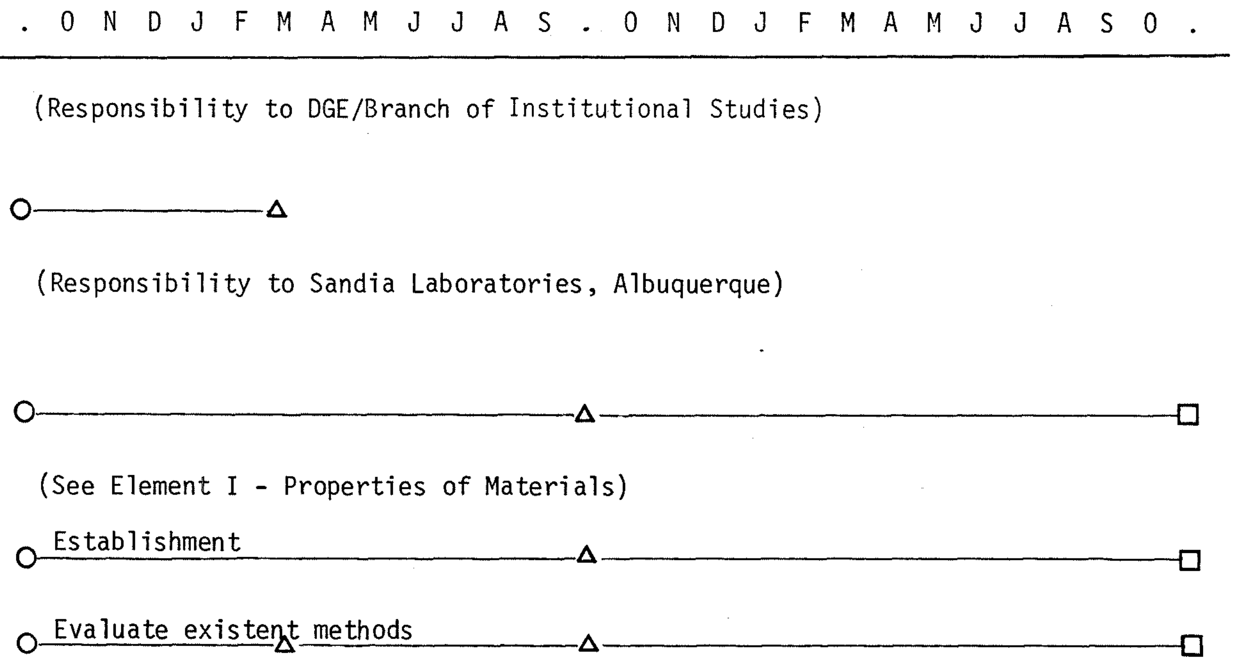
TABLE II-B-1

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Borehole Geophysics	1. Improve economic and institutional framework.	(Define impediments more clearly; refer to EIB.)
	2. Define parameters of value and interest.	a. Solicit opinions of operators. b. Document roles of parameters. c. Synthesize results. d. Report analysis. (NOTE: See 1976 Sandia Albuquerque workshop on logging.)
	3. Improve and ruggedize logging tools.	(Contact SLA)
	4. Establish and operate calibration wells.	a. Define conditions to be represented in calibration wells. b. Select sites for wells. c. Construct wells. d. Organize system to operate wells. e. Report results of use of calibration wells and program to calibrate and standardize tools.
	5. Conduct appropriate laboratory experiments related to log interpretation.	a. Concur in definition of parameters of value and interest. b. Evaluate effects of temperature, pressure, salinity on resistivity of saturated porous rock; relate to porosity, permeability, etc. c. Evaluate effect of fractures.

TABLE II-B-1

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Borehole Geophysics	6. Establish data bank of logs, cores, cuttings, fluid chemistry, and well performance.	a. Conceive of the organization and management of a data bank. b. Acquire data. c. Disseminate data and syntheses of data.
	7. Develop interpretive techniques for data collected from logging; anticipated parameters of interest are net pay, pore geometry, porosity, permeability, temperature, pressure, thermodynamic fluid quality, fractures present, matrix heat capacity, concentrations of selected chemical species, presence of certain gases.	a. Support selected investigations based on a theoretical approach. b. Evaluate existent methods. c. Develop interpretive correlations based on data base, laboratory studies and calibration holes. d. Report findings. e. Conceive and execute further evaluations of interpretive techniques.
	8. Disseminate results of program.	a. Develop "cook book" and nomographic articles. b. Hold appropriate seminars.

TABLE II-B-2



RESEARCH PROJECTS	. O N D J F M A M J J A S . O N D J F M A M J J A S O .
1. Improve economic and institutional framework.	(Responsibility to DGE/Branch of Institutional Studies)
2. Define parameters of value and interest.	○———△
3. Improve and ruggedize logging tools.	(Responsibility to Sandia Laboratories, Albuquerque)
4. Establish and operate calibration wells (or pits).	○———△———□
5. Conduct laboratory experiments.	(See Element I - Properties of Materials)
6. Establish data bank.	○ Establishment ———△———□
7. Develop interpretive techniques.	○ Evaluate existent methods —△—△———□

Legend:

○——— Proposed start of project/task.

□——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———□ Indefinite milestone.

ELEMENT II: DEFINITION OF RESERVOIR CHARACTERISTICS

CATEGORY C: WELL TESTING

Background

Well testing is conducted in order to estimate the size of a resource, to measure the parameters governing resource producibility, and to evaluate the condition of the well and flow capacity of the well. Parameters of interest include formation permeability, storativity, the presence of barriers and leaky boundaries, extent of well bore damage (if any), the presence of prominent fractures close to the well, the mingling of vertically separated productive layers, and so on. Included in testing are both testing under conditions where flow rates or well head pressures are carefully and deliberately controlled and testing under conditions where the reservoir is vented -- under conditions involving temporary completion of the well -- to pressure developed by only a fluid column in the bore (i.e. "temporary completion testing").

Well testing, as currently conceived, however, must be coupled with independently derived estimates of temperature in-situ, if estimates of the useful heat content of a resource are to be made. Hydraulic well testing consists of producing one or more wells at controlled rates and over periods typically ranging from a few hours to a few weeks and monitoring changes in pressure within the producing well itself or nearby observation wells. Temporary completion testing, such as drill stem testing, involves producing the reservoir using a temporary plumbing system and getting whatever information one can under primitive testing conditions.

Geothermal well testing and analysis is more difficult and less perfected than more conventional well testing techniques of hydrology and petroleum engineering. The geothermal environment commonly includes two-phase flow under non-isothermal conditions, and methods of interpretation of data for such situations are not yet perfected. Furthermore testing conditions in geothermal reservoirs are highly adverse for the reliable collection of good quality data. High temperatures and corrosive brines are particular, obvious problems.

A large body of literature is available on testing isothermal single phase systems because of the investigations of petroleum engineers and hydrologists over the past five decades. However, there is a general lack of methodology relating to the testing of non-isothermal, single and two-phase reservoirs. Nevertheless, under certain conditions (for example, when the temperature gradients within the reservoir are not steep), it is possible to use isothermal techniques for non-isothermal situations.

A single-phase reservoir may either be vapor-dominated or liquid-dominated. The dynamics of a vapor-dominated reservoir is similar to that of a gas reservoir. Available techniques for testing gas wells (see Odeh, 1967; Ramey et al., 1973, for a collection of key papers on the subject) not only enable estimation of permeability and storage parameters of the reservoir, but also help assess such additional features as well-bore damage, well-bore storage, turbulence effects, reservoir limits, effective drainage radius of the reservoir and reservoir depletion rates.

Numerous well-test techniques are available for studying isothermal, liquid-dominated systems. Some of the key references on the subject include those of Ferris et al. (1962), Hantush (1964), Lohman (1972), Matthews and Russell (1967), Narasimhan (1969), Odeh (1967), and Witherspoon et al. (1967). These tests are designed to evaluate overall reservoir properties (e.g., permeability and storage, reservoir limits, leakage, anisotropy, depletion) as well as to estimate near-well characteristics (e.g., well-bore storage, well-bore damage and skin effect, presence of master fractures, mingling of vertically separated producing horizons).

An important feature of well-testing is the interpretation of pressure transient data. Perhaps the most commonly used interpretation techniques are those of type-curve matching and asymptotic plots. Although type-curve matching has generally been achieved by eye judgment in the past, improved computer assisted curve-matching techniques are currently available which greatly generalize and increase the power of the method.

Successful execution of geothermal well-tests requires accurate instruments for measuring temperatures, pressures and flow rates at the well-head as well as downhole. For measuring downhole pressure, instruments are presently available with accuracy of 0.01 psi over a range of 0-10,000 psi. These instruments are self-recording, and readings can be obtained at intervals as small as one second. These instruments cannot tolerate temperatures greater than 300°F. For temperatures greater than 300°F, Bourdon tube devices are probably accurate to about 0.1 psi at best and cannot usually provide data at intervals of less than several minutes. Gas U.C. bubbler devices have accuracies on the order of a tenth of a psi and are especially subject to perturbation of pressure changes caused by the thermal expansion of the gas. Reliable temperature tools capable of functioning downhole for prolonged periods of time and providing continuous data appear to be currently limited to less than 200°C.

Statement of the Problem

To improve the existing capabilities of geothermal well-testing, there is need for further research work in regard to:

- equipment and instrumentation,*
- technique development,
- interpretation and analysis of data.

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*All projects and tasks involving hardware development will be coordinated with the Geothermal Logging Development Program at Sandia Laboratories, Albuquerque, New Mexico.

There is also need to define more carefully the spectrum of conditions (particularly pressure, temperature, and salinity) under which testing will be done.

Discussion of the Solution

Solution to the problem in general terms involves support for:

- more complete definition of testing conditions;
- development of equipment and instrumentation better tolerant of geothermal settings;
- development of new procedures for evaluating mass related and heat related properties simultaneously;
- improvement of techniques of interpretation and analysis.

Discussion of Possible Research Projects

Projects currently conceived under this category of research are listed in Table II-C-1. Several additional comments on this table are appropriate.

An important feature of improved equipment and instrumentation is not only that it be more accurate and precise but that it be capable of withstanding the geothermal environment for long periods of time (e.g., on the order of months).

Although there is a call for new testing techniques and procedures, this task is not detailed within this document. Ideas for new ways of testing are welcome and are allowed for under this heading. An example might be the development of a "standard" thrust nozzle for venting flow to atmosphere and instrumenting the nozzle to determine its actual thrust. If the thrust coefficient were known, it might be possible in this way to obtain a crude idea of the capability of a well.

There is a need for study of special heat and mass transport systems with initial, boundary, and internal conditions and constitutive laws peculiar to geothermal systems. An example is a reservoir with two-phase flow or with material properties varying spatially in some representative, prescribed manner. Such studies could lead to the development of appropriate well-test methods to identify and interpret these conditions. Fractures on both small and large scales and with various orientations are a further illustration of an interesting and incompletely understood component of geothermal systems.

Recent studies by Witherspoon et al. (1976) and Marine (1975) indicate that geothermal wells (and other deep, water wells) may respond to such extraneous causes as earth tides and microseismic activity. There is a need for development of techniques to interpret, if possible, these responses in terms of overall reservoir parameters. This category of testing may be called passive reservoir monitoring.

Decline curve analysis including review of documented declines in mass flow rates and enthalpy with time are also included here, although they may perhaps as well have been a part of the category "Modeling".

Project Objectives and Schedule

The project objective over the long term is to substantially improve capability to do those things noted in Table II-C-1 and discussed in the previous section. A possible schedule and the objectives to be realized as a consequence, is shown in Table II-C-2.

There should be an immediate review of those conditions of temperature, pressure, salinity, etc., that represent the range of values to be expected, the most likely conditions, etc.

Some additional projects should have demonstrated results during FY78. Included here are efforts on flow meters, automated data gathering systems, and apparatus for temporary completion testing. Also included should be demonstrated progress in improved capability to use well head data and to understand decline curves appropriate to geothermal resources.

Although some activity could be started on other topics also, significant output from them could be scheduled for FY79. Included here are improvements in pressure and temperature measuring tools, calorimetry systems, and mass flow rate measuring systems.

A level of effort attack on heat and mass transport analysis especially, and studies of new techniques should be started in FY78 and continued into FY79 if circumstances warrant. It is not possible at this time to lay out clear goals for work in the passive techniques of analysis but they, along with support for general improvement of analytical capability, should be supported also.

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TABLE II-C-1

RESEARCH CATEGORY	RESEARCH PROJECT*	RESEARCH TASK
Well Testing	1. Assess conditions in geothermal reservoirs that affect tool and analysis requirements.	
	2. Improved data gathering systems.	a. Develop improved pressure tool capable of 650°F, 0-5000 psi pressure, 0.0. accuracy, one second minimum readout interval.
		b. Develop improved temperature tool capable of 650°F, accuracy of 1°F, continuous operating up to 90 days.
		c. Develop reliable downhole flow meter for geothermal applications.
		d. Develop automated multi-well data gathering system.
		e. Develop improved calorimetry systems.
		f. Develop improved mass flow rate measuring systems, particularly for two-phase flow.
		g. Develop packing and isolation apparatus for downhole applications such as drill stem testing.
	3. Develop new testing techniques and procedures.	a. Techniques for simultaneous analysis of mass and heat movement.
		b. New techniques for crude estimates of well capability (cf. James Method).
	4. Development of interpretation and analysis methods for hydraulic well testing and for temporary completion testing.	a. Improve and extend the analytical capability for pressure and temperature analysis for uninvestigated initial, boundary, and internal conditions of the reservoir.
		b. Perfect the use of well head values instead of sand face values in analyses.
	5. Development of methods of analysis of data from passive reservoir response.	a. Analysis of earth tides.
		b. Analysis of response to microseisms.
		c. Decline curve analysis.

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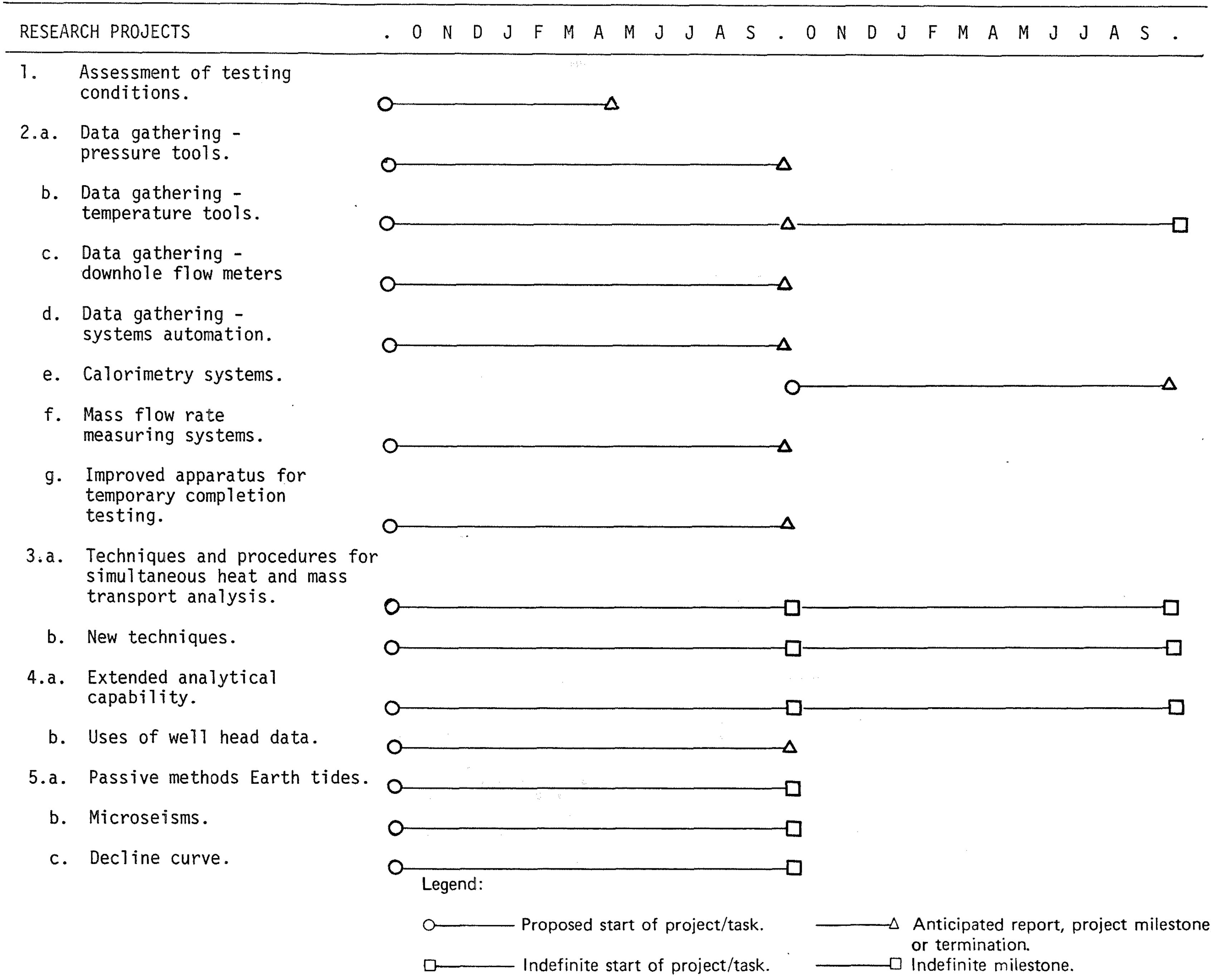
*All projects and tasks involving tool, hardware and material development will be coordinated with the Geothermal Logging Development Program at Sandia Laboratories, Albuquerque, NM.

TABLE II-C-2



RESEARCH PROJECTS . O N D J F M A M J J A S . O N D J F M A M J J A S .

1. Assessment of testing conditions.

2.a. Data gathering - pressure tools.

b. Data gathering - temperature tools.

c. Data gathering - downhole flow meters

d. Data gathering - systems automation.

e. Calorimetry systems.

f. Mass flow rate measuring systems.

g. Improved apparatus for temporary completion testing.

3.a. Techniques and procedures for simultaneous heat and mass transport analysis.

b. New techniques.

4.a. Extended analytical capability.

b. Uses of well head data.

5.a. Passive methods Earth tides.

b. Microseisms.

c. Decline curve.

Legend:

○—— Proposed start of project/task.

——△ Anticipated report, project milestone, or termination.

□—— Indefinite start of project/task.

——□ Indefinite milestone.

ELEMENT II: DEFINITION OF RESERVOIR CHARACTERISTICS

CATEGORY D: GEOCHEMICAL TECHNIQUES AND PROBLEMS

Background

Progress has been made in recent years in understanding the behavior of dissolved chemical species, noncondensable gases, and isotopes in natural geothermal systems. The development of geothermal reservoirs for energy production has enabled geochemical techniques to be applied in a few examples to gain an understanding of the behavior of geothermal reservoirs during exploitation. Additional opportunities for use of geochemical techniques in connection with exploitation of geothermal reservoirs clearly exist. In addition to greater utilization for reservoir analysis, work is needed to understand and remedy problems of mineral deposition (if they occur) caused by two-phase flow in the reservoir near a production well or by deposition from supersaturated fluids during injection of cooled fluids.

Geochemical research is currently quite active, because of the increased availability of flowing wells in producing reservoirs. Geochemical techniques are currently used at The Geysers, Cerro Prieto, and Wairakei to increase the understanding of these producing fields. On the basis of isotope and geochemical studies of surface samples, Truesdell and Fournier (1976) have shown that all of the waters of the various geyser basins in Yellowstone could be produced from a single parent water near 340° to 370°C. Wilson (1970) has analyzed the chemical data for Wairakei in order to relate thermal and chemical changes with production. Mercado (1976) describes the use of NA/K ratio to map reservoir temperatures and to infer fluid movements. Glover (1970) has used gas compositions to infer patterns of subsurface boiling during exploitation of the Wairakei geothermal field. Elders (1977) summarizes petrologic and isotopic studies of reservoir rocks as an aid to understanding reservoir mechanics. Recently, injected tracers have started to be used to investigate reservoirs. Einarsson and others (1976) have described an experiment of injecting a tritium slug into one well and watching the response in three producing wells, and a similar experiment has been run at The Geysers (Gulati, personal communication, 1976).

Statement of the Problem

Development of geochemical techniques requires a thorough understanding of the properties of dissolved chemicals, noncondensable gases, and isotopes in natural geothermal systems. For some constituents and some situations, adequate sampling and analytical techniques are available. However some situations require further research (e.g., hypersaline brines). There is currently a scarcity of experimental data on properties such as reaction rates, for example, for chemicals in water flowing through a porous medium at the high velocities expected during exploitation. Improved understanding of dispersion, partitioning between vapor and liquid phases, and solution and redeposition are needed to aid in interpreting behavior of fluids within a reservoir. Such understanding is currently not fully available, but should it become available, it would be immediately useful in analysis of specific sites and in the formulation of models for reservoir performance. An improved ability to monitor and forecast reservoir performance should be invaluable in planning optimum recovery of energy from a geothermal resource.

Discussion of the Solution

Solution to the problem involves support for:

- Synthesis of the experience to date in the use of geochemical techniques for exploitation application.
- Investigations of the behavior of chemical species, dissolved gases, and isotopes under various production situations.

- Studies of petrology and isotopes of reservoir rocks.
- Additional applications to geothermal reservoirs of geochemical techniques currently believed to be well understood.
- Incorporation of understanding of the behavior of reacting and non-reacting constituents into mass and energy transport codes.
- Still additional applications as understanding of the basic behavior of isotopes improves.

Discussion of Possible Research Projects

Projects currently conceived under this category of research are listed in Table II-D-1.

Although there is experience with geochemical techniques in geothermal reservoirs, this experience and other experience as may be discovered has never been reviewed and synthesized from an exploitation point of view. Such an effort needs to be undertaken.

An improved understanding of all constituents of interest in geothermal resource exploitation is a vast subject. However, it must be undertaken if the capability of geochemical techniques is to be more fully understood and extended into more useful ways. Projects under this effort could be packaged into very special investigations each of which is dedicated to one aspect of the behavior of one chemical species, e.g. the reaction rates of silica under various conditions.

Existent understanding of the behavior of many chemical systems appears to be adequate to justify applications to specific sites in order to help with practical problems.

Project Objectives and Schedule

The objectives of this project, as defined in this document, are 1) to determine the currently existing capability and applicability of geochemical principles and techniques for use in exploitation of geothermal resources, 2) to enhance this capability through improved understanding of the behavior of dissolved chemicals, noncondensable gases, and isotopes and through continued application for exploitation purposes, and 3) to understand and solve chemical problems associated with injection and production of fluids.

A schedule from the project is shown in Table II-D-2. There is a call for support in FY '78 for a synthesis and extension of work applicable to exploitation purposes. Support should also begin immediately for improved understanding of behavior of tracers.

The project in geochemical techniques relates to several other projects. These include numerical remodeling and site specific studies.

Interfaces

Several programs currently being developed (October 1977) by the Brine Geochemistry Program within the Utilization Technology Branch of DOE/DGE interface with this program element.

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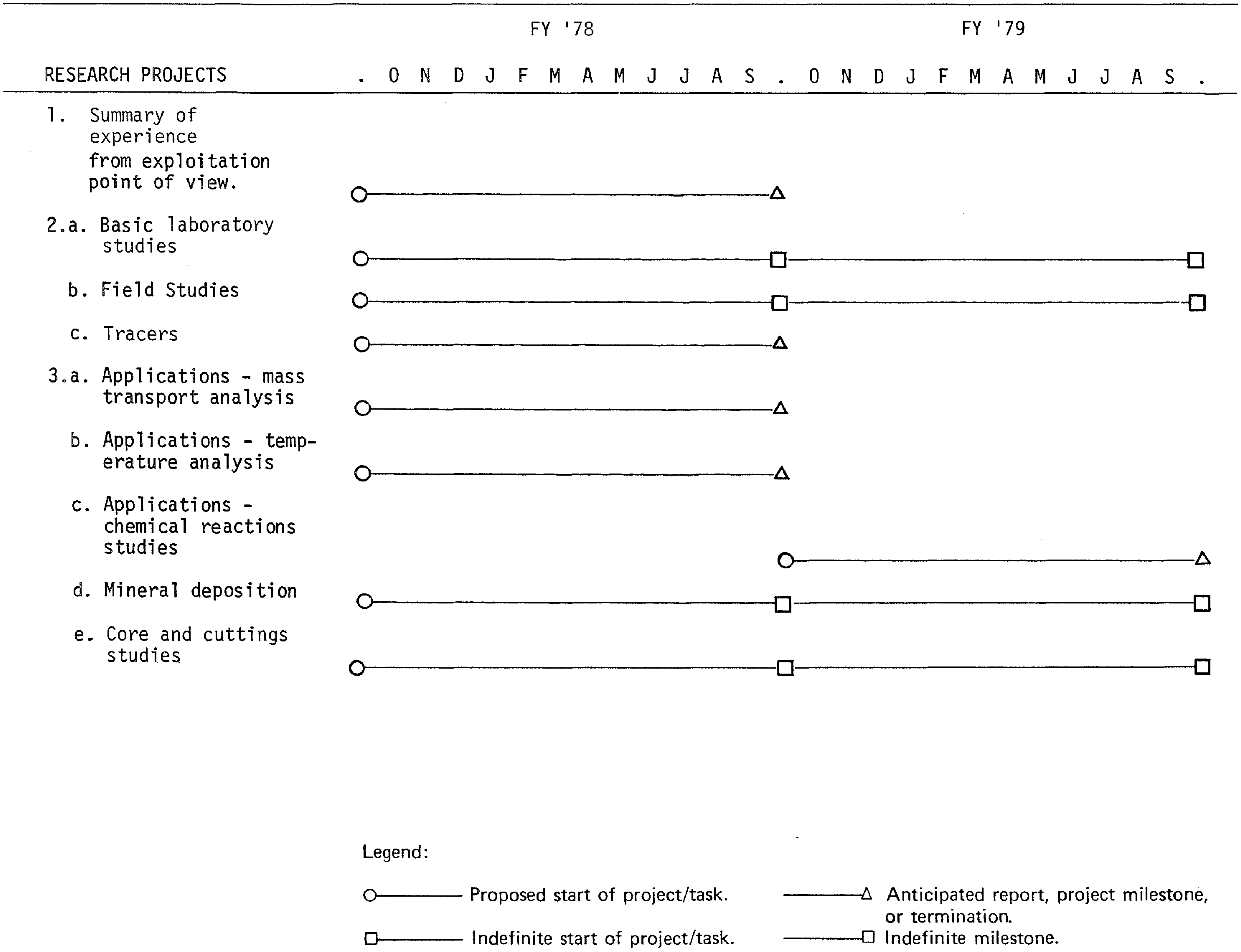
TABLE II-D-1

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Geochemical Techniques and Problems	1. Summarize experience in the use of geochemical principles and techniques for exploitation applications including a data base and relate to need for work in "2" (below).	a. In connection with studies of mass movement.
		b. In analyses of temperature distributions.
		c. In connection with problems of precipitation within geothermal systems.
	2. Investigations of basic geochemistry, including not only equilibrium situations but those having kinetic effects as well.	a. Laboratory studies of reactions rates, partitioning, dispersion characteristics, etc., of chemical species of interest with a view to usefulness in understanding mass movement, temperature distribution, and chemical reactions in geothermal systems. Specific studies include phase behavior of dissolved gases, physical properties of brines, etc.
		b. Field studies of the above.
		c. Investigate candidates to be used as reactive and non-reactive injected tracers.
	3. Application of geochemical techniques and principles.	a. Mass movement analysis.
		b. Temperature distribution studies.
		c. Chemical reactions studies, especially corrosion.
		d. Mineral deposition studies, especially the formation of scale.
		e. Core and cuttings studies.

TABLE II-D-2


FY '78
FY '79
RESEARCH PROJECTS
. O N D J F M A M J J A S . O N D J F M A M J J A S .
1. Summary of experience from exploitation point of view.
2.a. Basic laboratory studies
b. Field Studies
c. Tracers
3.a. Applications - mass transport analysis
b. Applications - temperature analysis
c. Applications - chemical reactions studies
d. Mineral deposition
e. Core and cuttings studies
Legend:
Proposed start of project/task.
Indefinite start of project/task.
Anticipated report, project milestone, or termination.
Indefinite milestone.

ELEMENT III: DESCRIPTION OF EXAMPLE RESERVOIRS

CATEGORY A: FUNDAMENTAL STUDIES OF GEOTHERMAL PHENOMENA

Background

This category of research addresses a complex of phenomenology that describes the behavior of geothermal reservoirs at their most fundamental level. Included here are considerations such as the rate of heat flux from the primary source of geothermal heat to the exploitable geothermal reservoir, the acquisition of data on the viscosities and surface tensions of saline solutions at elevated temperatures, the development of a statistical data base for drilling experience for the treatment of stochastic analyses, etc.

Indeed a great deal of research of this vein is currently being done and a purpose of this category is to recognize formally the importance of this effort. However, although directed at basic phenomenology, this category is not intended to be divorced from eventual application to practical procedures in the development of geothermal resources.

The rationale for proposing a category of this kind is the same rationale for support of any effort in basic research: namely, the better understanding of the science applicable to a given subject the better basis there is for developing a technology for dealing with the subject.

Statement of the Problem and Its Solution

The nature of this category of research is so diffuse that it is difficult to specify what the "problem" is. A reasonable statement, however, might be to say that the problem is to support research in the science of geothermal resource development at a not too exactly defined level of effort.

Discussion of the Solution

It would be desirable to develop the level of understanding of geothermal resources to that level existent in the petroleum industry. The scope of such an effort is boundless. Nevertheless, the following are example topics:

1. The conceptualization of a geothermal resource.
2. The heat source for particular geothermal reservoirs.
3. All physical properties that bear on the thermodynamic behavior of the rocks and brines found in geothermal reservoirs.
4. All physical properties bearing on the fluid properties of brines.
5. Studies of a stochastic nature relating to forecasting the behavior of geothermal reservoirs when they are produced.
6. Rock-water interactions and their consequence to the fluid phases present in geothermal reservoir. (Note also the section on Geochemical Techniques and Problems.)
7. Mathematical techniques that are of practical significance primarily for mathematical formulation of the physics to model, mass, energy and reactants transport simultaneously.

Schedule

This category of research differs from others inasmuch as there are no specific projects listed. It is recommended that some level of effort (e.g. 20%) be directed toward ongoing fundamental research.

Interfaces

To be effective this program category must interface with all other program categories;and,in fact,a requirement for support should be that the researchers relate their effort to more programmatic endeavors.

ELEMENT III: DESCRIPTION OF EXAMPLE RESERVOIRS

CATEGORY B: FIELD CASE HISTORIES

Background

The early history of the petroleum industry in the United States was marked by numerous descriptions of the occurrence of hydrocarbons in various fields. This "experience base" formed the empirical insight to those who were responsible for the development of new fields. Such an experience base is needed for the geothermal industry.

In fact, there is currently a very substantial amount of geological information about geothermal resources (for example the Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources). Of these studies, however, there are relatively few that have been conducted from the point of view that an exploiter of the resource might want to have. There are few reports showing such features of importance to exploitation orientated readers as temperature distribution, porosity-feet throughout the reservoir, etc. or in general all those things one would want to know in making decisions about the size of the resource and about construction of a system of wells for producing it.

Examples of geothermal reservoirs that are well documented from an exploitation point of view will perhaps be more useful as a guide for planning development of new geothermal resources than will be theoretical studies. Accordingly, it would be very useful to have such examples.

Statement of the Problem

The problem for this category is that there is a demonstrable use for and a need for more site specific case studies of geothermal resources in order to establish an "experience base" to which one can refer in planning development of geothermal resources. Opportunities for such documentation are available at a number of sites throughout the world. The data from these locations need to be collected, synthesized, and, if possible, generalized.

This category should not be confused with another DOE/DGE program known as the "Case Studies Program". The category being discussed here assumes that a data base will be available at no cost. The Case Studies Program emphasizes the acquisition of new data at partial federal government expense.

Discussion of the Solution

The solution to the problem calls for support in at least two general areas of work:

- support for comprehensive documentation of site specific studies
- support for synthesis of all sites so documented.

Documentation of specific sites should address those features of the resource of primary interest to a developer:

- distribution of temperature
- distribution of pressure
- distribution of porosity
- distribution of permeability
- distribution of chemical species
- energy and mass recharge systems.

Discussion of Research Projects and Schedule

There are currently several site specific studies being conducted under sponsorship by DOE/DGE. Included here are those studies listed in Table III-B-1. They should be continued. In addition, opportunities should be created to study additional sites, should they be proposed for study.

As the number of well documented site specific studies grow, there should be increasing possibilities for synthesizing and generalizing the results obtained. There should be support for such activity in FY79.

Interfaces

This activity, to be done well, should interface with all other discipline oriented program elements. Although no element is excluded from a possible tie-in, possibly this element will not relate to the Economics section.

The opportunity to relate this activity to exploitation strategies should be encouraged.

TABLE III-B-1

RESEARCH CATEGORY	RESEARCH PROJECTS	RESEARCH TASKS
Field Case Histories	1. Comprehensive documentation of specific sites.	a. Study of East Mesa, California
		b. Study of Niland
		c. Study of Heber
		d. Study of Raft River
		e. Study of Roosevelt Hot Springs
		f. Study of Valles Caldera
		g. Study of Cerro Prieto
		h. Study of Wairakei
		i. Study of Coso Hot Springs
		j. Study of Hawaiian Geothermal Project
		k. Others
	2. Synthesis, generalization and development of conceptual models from field case histories. Note: Review Task Force recommended this task be a part of section "Fundamental Studies."	

TABLE III-B-2

		FY '78													FY '79												
RESEARCH TASKS	.	O	N	D	J	F	M	A	M	J	J	A	S	.	O	N	D	J	F	M	A	M	J	J	A	S	.
1.a. East Mesa					☐	—	—	—	—	—	—	—	—	☐													
b. Niland					☐	—	—	—	—	—	—	—	—	☐													
c. Heber					○	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
d. Raft River					☐	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
e. Roosevelt Hot Springs					☐	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
f. Valles Caldere					☐	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
g. Cerro Prieto					☐	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
h. Wairakei					☐	—	—	—	—	—	—	—	—	☐													
i. Coso Hot Springs					☐	—	—	—	—	—	—	—	—	☐	—	—	—	—	—	—	—	—	—	—	—	—	☐
2. Synthesis, generalization and development of conceptual models.														○	—	—	—	—	—	—	—	—	—	—	—	—	☐

Legend:

○——— Proposed start of project/task.

☐——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———☐ Indefinite milestone.

ELEMENT IV: MODELING THE BEHAVIOR OF GEOTHERMAL SYSTEMS

CATEGORY A: ANALYTICAL MODELING

Background

In planning for the development of a geothermal resource, it is desirable (and perhaps even necessary) to have methods available to understand and anticipate the behavior of the resource including those things that result from efforts to exploit it as well as phenomena that occur naturally. Models, of course, provide such a capability. Analytical models in particular are useful for a number of reasons:

- Appreciation of the governing equations or their degenerate form provides insight into the physical processes that dictate behavior of the reservoir.
- Forecasts of reservoir performance, etc. can be quickly and fairly easily tabulated if the governing equations can be solved for the boundary and initial conditions of interest.
- Results of solutions are valuable in calibrating numerical models.

Analytical models also have limitations, however. A particular limitation is that in order to be tractable, the governing equations and boundary conditions must be simplified; and, as a consequence, the physical situation may not be very realistic.

Several analytical models of use in geothermal resource exploitation have been developed or are currently under development. Examples include the following:

- Ramey (1962) analyzed the heat losses for flow in a well using the approximation that heat conduction in the rock is only radial and the resulting formulation is applicable to many situations.

- Some of the solutions for analyzing short-time pressure histories in wells have been obtained analytically (e.g., Gringarten, Ramey, and Ragahavan, 1974).
- Bodvarsson (1969) solved the problem of heat transfer to a fluid moving in a crack in an infinite medium.
- Nathenson (1976) analyzed the effects of a step change in water flow on an initially linear profile of temperature in a porous medium to study the magnitude of temperature changes that could be expected due to increased recharge to a geothermal area.
- Kassoy (1976) studied the flow in a fault zone of finite thickness and, by neglecting end effects, established the effect that geometry of a fault zone has on the form of the flow.
- Kassoy and Zebib (1975) as well as Strauss and Schubert (1977) have studied the onset of convection in a porous media.
- Cheng and Lau (1974) used perturbation methods to simplify the equations for studying convection.
- Gray and O'Neil (1976), Blake and Garg (1976), as well as Assens (1976), studied the derivation of the governing equations for mass and energy transport in a porous medium.

Statement of the Problem

The usefulness of understanding important, governing physical processes and of capabilities available because of analytical modeling has been demonstrated in the petroleum industry. However, such a condition of insight and application has not been established completely in the geothermal industry. There is a need for review of the mathematical formulation of the physics and chemistry that describe the behavior of geothermal systems insofar as these are known. There is a need for recognition of the most important simplification of this formulation. There is need also for support of solutions to meaningful problems including those that are immediately practically applicable (e.g., pressure buildup for simple geometries, etc. in a well) and those that are used to calibrate or verify more general numerical models. It is not easy to know or list in advance all the problems that could usefully be solved. Inasmuch as such solutions are usually not too expensive to support (compared with field programs, for instance) a fairly large number of activities in this category could be supported.

Discussion of the Solution

In general terms the solution to this problem calls for support in the following areas:

- Formulation and study of the most comprehensive general equations for the behavior of energy and mass transport in porous, fractured media.
- Specific, identified analytically tractable problems. (Some of these are discussed in the following section.)

The value of analytical solutions to problems that test various aspects of numerical solutions should not be overlooked. Such use for analytical solutions is important.

Discussion of Possible Research Projects

A number of research projects that fit within this category are listed in Table IV-A-1. Several comments on this table are appropriate.

There is a need for formulation and incisive analysis of the basic equations for mass and energy transport in geothermal systems. Everyone today deals with some simplification of these equations. One may wonder how serious such simplifications are -- or how difficult would be any effort to solve fully rigorous formulations.

Certain problems have in the past been tractable in a meaningful way by analytical methods. Included here are problems in short term well behavior. Simple problems in heat transfer and problems in convection and conduction or both. Support should continue for these as well as other specific analytical problems of defensible value.

Project Objectives and Schedule

The objectives of this category of research are to more clearly illuminate the mathematical formulation of the physical and chemical behavior of geothermal systems. In addition, this category of research should lead to a better understanding of certain problems amenable to analytical solution. These include the following (that are also slated for support in FY78):

- well pressure behavior;
- well temperature behavior;
- heating of a borehole;
- heat flux across a fracture face;
- conduction and convection in layered media;
- conduction and convection in situations where a boundary condition is imposed by a magma body.

This category of research should also allow for the submission of problems not specifically mentioned in this document.

Support should continue in FY79 for more studies in well behavior, and specific efforts should be started for work on convective instabilities and on heat flux into fluids in the pores of porous media.

The proposed schedule for this program category is shown in Table IV-A-2.

Interfaces

As noted implicitly in the preceding narrative, this program element relates to numerical modeling and well testing. Its results should, of course, be very valuable to analysis of specific sites and situations.

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TABLE IV-A-1

IDENTIFIED TASKS (AND OTHER COMMENTS)

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASKS
Modeling the behavior of geothermal systems. Analytical modeling.	1. Formulation and analysis of the basic equations for mass and energy transport in geothermal systems.	Formulation as well as review of significance of terms in the equation.
	2. Analysis of short term well behavior. (Note the relationship of this project to the Research Category II.C, "Well Testing.")	a. Well response with respect to pressure for uninvestigated boundary initial and internal conditions, e.g., two-phase, fractured reservoir. b. Temperature response, etc. c. Combined temperature pressure responses, etc.
	3. Problems in heat transfer.	a. Heat extraction through a fracture face. b. Heating of a borehole with radially varying thermal properties. c. Heat flux to fluid contained in pores of different configurations, e.g., tabular, cylindrical, toroidal, etc.
	4. Problems in conduction and convection	a. Vertical convection in layered media. b. Conduction and convection between magma and country rock. c. Studies of convective instabilities and their consequences on mineralization.

TABLE IV-A-2

	FY '78												FY '79											
RESEARCH TASKS	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1. Formulation and analysis of basic equations.							0	—	—	—	—	△												
2.a. Analysis of well behavior - pressure.							0	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
2.b. Analysis of well behavior - temperature.							0	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
2.c. Other analyses.							0	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	□
3.a. Heat transfer - fracture face.							0	—	—	—	—	△												
3.b. Heating of a borehole.							0	—	—	—	—	△												
3.c. Heat flux in porous media.												0	—	—	—	—	—	—	—	—	—	—	—	□
4.a. Conduction and convection - in layered media.							0	—	—	—	—	□												
4.b. Conduction and convection due to magma source.							0	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	△
4.c. Convective instabilities.												0	—	—	—	—	—	—	—	—	—	—	—	□

Legend:

○———	Proposed start of project/task.	———△	Anticipated report, project milestone, or termination.
□———	Indefinite start of project/task.	———□	Indefinite milestone.

ELEMENT IV: MODELING THE BEHAVIOR OF GEOTHERMAL SYSTEMS

CATEGORY B: NUMERICAL MODELING

Background

Numerical modeling calls for mathematical simulation of processes occurring in natural systems. Modeling is carried out by incorporating known and relevant physical and chemical principles into a mathematical framework. Solutions for any given conditions are obtained in whole or in part by numerical methods.

Various numerical techniques are currently available for numerical modeling. These techniques include: finite difference methods, finite element methods, and integrated finite difference methods.

The advantage of numerical modeling over analytical modeling is that it can handle complex problems involving a large number of variables. Its advantage over laboratory physical modeling is that, once operational, a numerical model can handle a wide spectrum of conditions at minimal extra costs.

The disadvantages of numerical modeling are fairly well known. They include:

- Intrinsic numerical problems, such as dispersion, oscillations, convergence and questions about uniqueness of solution.
- The models are usually deterministic but the required parameters are generally poorly known and the initial conditions are somewhat uncertain. (These disadvantages are also common to other modeling methods.)
- Solutions are problem-specific.

Research in numerical modeling may be classified into these areas. These include:

a. modeling the physics of geothermal reservoirs

b. modeling chemical phenomena associated with them,

c. improvement of solution techniques.

Under the heading "modeling of physics", the study of single phase systems is well advanced with the work of Sorey, Lippmann, Lasseter, Mercer and Faust, and others. (Further research still needs to be done to understand compaction and land subsidence processes, but this topic is under the "Subsidence Management Program". Work remains to be done in the two phase heat and mass flow simulation. Although several numerical models have been developed by various groups (Mercer and Faust, Lasseter, S^3, Intercomp), these should be carefully validated and compared with each other by applying them to the same problems. Also, many two-phase processes in geothermal reservoir still remain to be studied and understood; for instance, the onset of boiling and its effect on relative permeability has not been addressed properly in a reservoir simulator. As improved understanding is acquired, it should be incorporated into the modeling.

Studies on the physics of well-bore region and fracture systems are also very important. Certain progress has been made in single-phase fractured systems (Schroeder and Kasameyer (1975), Narasimhan, Pinder) but further work is necessary. Attention should be directed towards large connecting fractures near the well-bore, because random fractures far away can be approximated by a porous medium with an effective porosity, permeability, and conductivity (cf. Pinder, 1975). Two-phase fractured systems still need to be studied, although two-phase flow in the well-bore has been studied to some extent by Gould, Elliot, Schroeder, and Nathenson.

Simulation of chemical reactions coupled with fluid and heat transfer is a major open problem although some work has begun already (S^3, Intercomp, Apps, and others). Much basic information is lacking to make a proper numerical model, such as rock-fluid interaction rates, data on precipitation rate, and changes in permeability due to precipitation, etc. It may be necessary to wait for further laboratory and field studies before this kind of numerical modeling can fruitfully be undertaken. This subject is probably the weakest area in our understanding of reservoirs.

Various numerical techniques are currently available for numerical modeling, such as Finite Difference Methods (van Poolen, Mercer and Faust, Watts), Finite Element Methods (Pinder, Mercer, Neuman), and Integrated Finite Different Method (Edwards, Lasseter, Narasimhan). Some efforts have been made (Narasimhan and Neuman) to develop new techniques. Although short-term breakthroughs are not expected, one should hope for more powerful numerical techniques for the next generation of simulations.

Statement of the Problem

Problems in numerical modeling of geothermal reservoir performance can be placed in the following categories:

- Improvement in understanding of the basic physical and chemical phenomenology that are necessary to meaningfully model the behavior of geothermal reservoirs.
- Evaluation of simulators that are reported to be able to model the behavior of geothermal reservoirs, and the identification of their limitations.

- Improvement of modeling capability.
- Improvement of numerical methods.

Discussion of the Solution

Solution of the problem of improved numerical modeling of geothermal reservoirs involves activities:

1. To understand better the significant processes occurring in geothermal reservoirs.
2. To evaluate the capabilities of existent numerical models more fully and adequately.
3. To improve these models and/or develop new models to better simulate geothermal reservoir performance.
4. To disseminate these results and improved capabilities and to call for support for advanced numerical techniques if experience justifies such a course of action.

This program element focuses on items 2 and 3 but will, of course, be cognizant of work under item 1 (which should be done under other program elements).

Project Element Objectives

The objectives of this element of the program are to:

- Encourage the elucidation of basic physical and chemical phenomenology with a view to eventually incorporating these ideas into a numerical model.
- To evaluate the current status of numerical models for geothermal reservoir performance.
- To improve upon this status as appropriate.

- To call to the attention of applied mathematicians the needs, if any, of improved numerical methods.

Discussion of Possible Research Projects

Projects conceived under this category of research are listed in Table IV-B-1. Several additional comments on this table are appropriate.

At the present time there are a variety of numerical models for the simulation of geothermal reservoir performance in the public domain. The strengths, weaknesses, capabilities, etc. of these codes need to be evaluated. What problems can the codes handle? Are the codes computationally efficient? Are their outputs intelligible, etc.? There is an obvious need to take stock of the purported capability.

The fundamental reasoning behind the construction of a numerical model needs to be fully elucidated. What form does the most general differential equation describing mass and energy transport within a geothermal reservoir have? How unphysical are the simplifications made in order to develop a tractable form of this equation?

There is a strong need for the improvement of numerical models, such as chemical transport and reactions, two-phase behavior and the consequences of fractures.

The application of existent codes to important, hypothetical models is more than an abstract exercise if the hypothetical models are well chosen. The public experience in geothermal reservoir production is so limited at present that analysis of long term behavior of various hypothetical systems of producers and reinjectors (e.g. a five-spot) would be very enlightening. Such exercises should also call attention to the kind of phenomena one might be alert for in a real situation as well.

Discussion of Expected Results and Milestones

Table IV-B-2 shows a schedule in which certain milestones are noted. Work should begin immediately in the evaluation of existent codes and of the basic physical and chemical phenomenology that should be or could be incorporated into viable and practically useful codes. Although of lower priority (as indicated by their indefinite "milestones"), work should also be directed at 1) an improved two-phase, non-isothermal code; 2) the role (or roles) of fractures; 3) coupling of reservoir and well-bore flow codes; and, 4) application of existent codes to hypothetical but meaningful problems. Efforts to simulate important chemical phenomena can probably be delayed to Fiscal '79.

Interfaces

The results of research in numerical modeling apply to many other obvious elements of the program. Especially important is the relationship to the study of specific sites. Input to research in numerical modeling came mainly from fundamental studies. In connection with applications of numerical modeling, inputs from well testing and well-bore logging are vitally important in setting up boundary, and initial conditions.

TABLE IV-B-1

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Numerical modeling	1. Evaluation of existent codes.	
	2. Evaluation of the basic phenomena governing reservoir behavior.	a. Physical phenomena
		b. Chemical phenomena
		c. Exploitation design
	3. Improvement of numerical models.	a. Modeling of two-phase, non-isothermal systems.
		b. Consideration of effects of fractures near bore region, one- and two-phases.
		c. Effects of fractures away from bore, one- and two-phases.
		d. Simulation of important chemical phenomena.
		e. Coupling of reservoir and borehole transport problems.
	4. Application to hypothetical but important production/reinjection exploitation schemes.	
	5. Inverse problem.	
	6. Improved numerical techniques.	a. Study of numerical dispersion.

TABLE IV-B-2

RESEARCH PROJECT	FY 78												FY 79											
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
1. Evaluation of existent codes.				○	—	—	—	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
2.a. Evaluation of basic phenomenology - physical.				○	—	—	—	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
b. Evaluation of basic phenomenology - chemical.				○	—	—	—	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
c. Evaluation of basic phenomenology - exploitation design.													○	—	—	—	—	—	—	—	—	—	—	□
3.a. Improvement of numerical models - two-phase, non-isothermal.				○	—	—	—	—	—	—	—	□												
b. Fracture effects - near bore region.				○	—	—	—	—	—	—	—	□												
c. Fracture effects - away from bore.				○	—	—	—	—	—	—	—	□												
d. Simulation of important chemical phenomena.													○	—	—	—	—	—	—	—	—	—	—	□
e. Coupling of reservoir and borehole problems.				○	—	—	—	—	—	—	—	□												
4. Application of existent codes to hypothetical but meaningful problems.				○	—	—	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	□
5. Inverse problem				○	—	—	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	△
6. Improved numerical techniques				○	—	—	—	—	—	—	—	□	—	—	—	—	—	—	—	—	—	—	—	□

Legend:

○——— Proposed start of project/task.

□——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———□ Indefinite milestone.

ELEMENT IV: MODELING THE BEHAVIOR OF GEOTHERMAL SYSTEMS

CATEGORY C: PHYSICAL MODELING

Background

Physical modeling, as used here, refers to the use of physical models to simulate the behavior of geothermal reservoirs. The theory of scale modeling has been appreciated for quite some time, and the application of such thinking to earth sciences problems dates to at least the 1930's (Hubbert, 1937). Practical constraints on scale modeling have long been recognized too, however. Consequently there has been an endeavor to use "almost scale" modeling judiciously in lieu of exact scaled models. In at least one case, estuarine hydrology of San Francisco Bay, investigators have been successful using this approach (Schrock, personal communication, 1976).

There have been at least two efforts in physical modeling (Turcotte et al., 1976), one of which addresses the question of appropriate scaling (Schrock and Laird, 1976).

The advantages of physical modeling are several. First, they give the researcher a different, truly physical sense (contrasted with an abstract sense), of the phenomena being investigated. Second, they give real and continuous results; even if not truly scaled, they are useful experiments against which analytical and numerical results may be compared. Third, there is some argument that physical models can handle mathematically intractable problems. On the other hand, the experiments are cumbersome to set up (Schrock and Laird, 1976, p. 219); and unless one is judicious in selection of a suite of experiments, the results of the effort can have only a limited scope of applicability for the effort expended.

Physical models are analogue models that serve to illuminate patterns of mass and heat transfer.

Statement of the Problem

Although the theory of scale modeling is known and several applications of physical modeling have been reported, there has not been a comprehensive analysis of the theory of scale modeling as it might apply to real, specific geothermal systems. Some researchers question the value of physical modeling at all. Their usefulness might better be defended if 1) the theoretical basis of scale modeling (or almost scale modeling) were more fully elucidated from the point of view of one involved in geothermal resource exploitation, and 2) if the modeling were applied to specific real sites.

Discussion of the Solution

There is need for support for an effort to more fully document the applicability of scale modeling <u>and</u> almost scale modeling to geothermal systems. There is also need for support for some application and experiments to evaluate the usefulness of this approach to modeling.

Research Projects and Schedule

Three major research projects have been identified. These are shown in Table IV-C-1. Some comments on the table are called for.

The theory of scale modeling is known and has been discussed succinctly by Schrock and Laird (1976). However, a more expanded discussion should be useful and a discussion of almost scale modeling from a geothermal point of view is needed.

As already mentioned, some experiments have been carried out. There is a need, however, for correlation of the results of such modeling with an analytical or numerical model in order to compare the difference.

Finally, there should be some effort to conduct an experiment of a specific geothermal site. It would be reasonable to expect some useful results from such an effort, were it no more than the realization that the boundary conditions are imperfectly known at best.

The schedule proposed for this category of work is as shown in Table IV-2-C.

Interfaces

This program element should relate closely to analytical and numerical modeling and to site specific studies.

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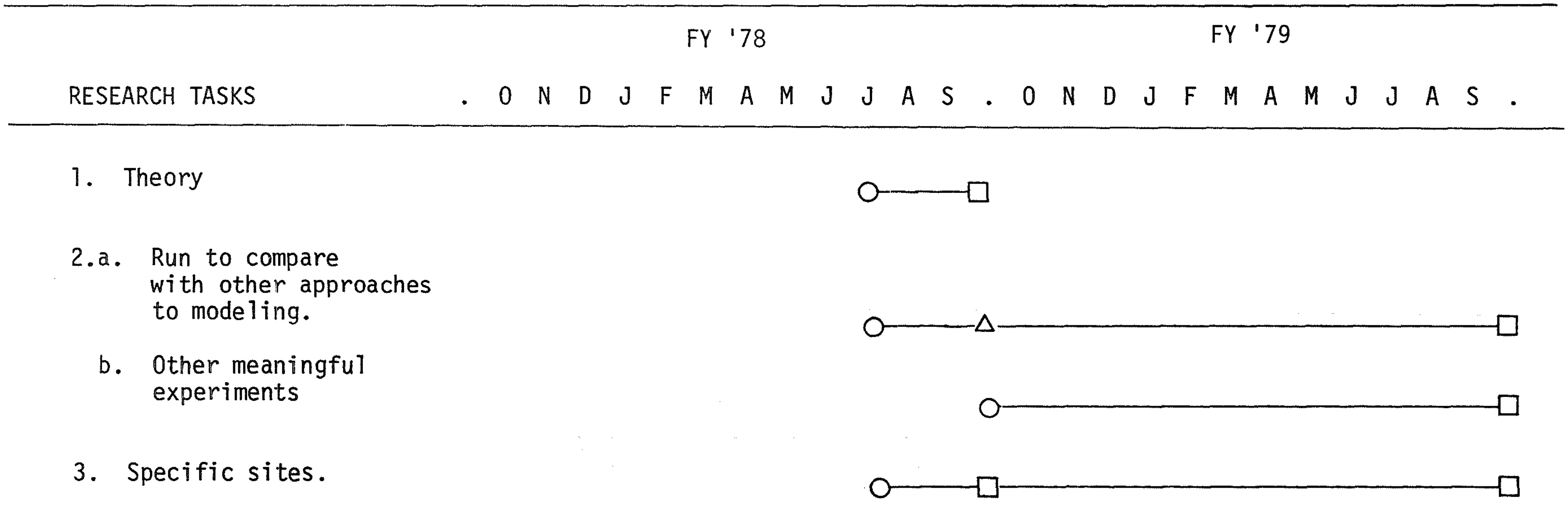
TABLE IV-C-1

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Physical Modeling	1. Define more fully the theory of scale modeling for geothermal systems.	
	2. Conduct experiments.	a. For comparison with analytical or numerical modeling.
		b. Other interesting series of experiments.
	3. Investigations of specific sites using physical modeling.	

TABLE IV-C-2



Legend:

○———— Proposed start of project/task.

□———— Indefinite start of project/task.

————△ Anticipated report, project milestone, or termination.

————□ Indefinite milestone.

ELEMENT V: EXPLOITATION STRATEGIES

Background

Strategies exist for the exploitation of site specific natural resources such as copper, oil and gas, etc. For instance, there are several recognized procedures for developing hydrocarbon accumulations around the margins of salt domes. Presumably there has also been a rationale for the development of each of those geothermal resources that have been developed to date throughout the world. However, there is no well known elucidation of these rationales nor has there been any analysis of alternatives that could perhaps have been more effective had they been followed during exploitation. For instance, is it necessary to drill some specified number of wells and flow them full bore for a 1000 hours in order to proceed with construction of a power plant. Is the waste of energy necessary or justified? How many wells are needed at any point in time to safely assure a fuel supply to a power plant of a given size? Where should the power plant be located with respect to the geothermal resource? In any program involving uncertainties, so called "good" strategies are obviously important to identify and follow so as to minimize the pain associated with 20-20 hindsight.

Statement of the Problem

Inasmuch as development of a geothermal resource involves a complex of systems (e.g. a "fuel" producing system of wells, an energy conversion system, a disposal system, an electrical distribution or heat distribution system, etc.), there clearly are many options for exploitation or, in other words, many possible strategies, not all of which are equally effective. If, in fact, there have been strategies for the development of specific geothermal resources, they are not widely known. Furthermore, there has not been sufficient research and reporting of this topic to have allowed comparison of rationales used with other possibilities in order to assess how well conceived the exploitation program might have been.

There is need for review of strategies employed to date (if they can be reconstructed) and for analysis of new strategies in geothermal resource development in general.

Discussion of the Solution

The solution to the problem regarding exploitation strategies involves the following components:

- determining what has been done with regard to exploitation strategies in other mineral industries
- determining strategies used in geothermal resource development to date
- reviewing these strategies and analyzing real or hypothetical procedures for optimizing the exploitation of geothermal resources with respect to some stated criteria; e.g. maximum profit, minimum investment, maximum energy recovery, minimum disturbance to the environment, etc. or some combination of these criteria.

The solution also calls for providing information to other elements in the program to emphasize those needs which require improvement to allow for improved strategies.

Discussion of Possible Research Projects

Table V-1 lists several research projects in this program element, and a few comments on the table are called for. There is, as implied above, a need for review and assessment of existent strategies that could have or have been used in geothermal resource exploitation. These activities could be combined into one effort.

A project for new strategies and for alternatives to strategies that have already been used should also be undertaken. An obvious key feature in making geothermal resources a viable competitive source of energy is that they be exploited effectively. Such a realization will not come unless there are analyses of the plans and decisions that are involved to help to assure that they have been the best possible plans and decisions.

The program also calls for opportunities to conduct specific case studies in order to illustrate strategies used. Perhaps the most acceptable and most noticed research done in this program category will be in connection with specific case studies. Such case studies could be combined with geologically oriented case studies.

Research Schedule

The suggested schedule for research on the research projects noted in this element are shown in Table V-2. Review and assessment of existent strategies should be undertaken in FY78. Work may begin in FY78 on alternative strategies and case studies if opportunities and available funds allow. Strategies based on "non-business" criteria should be put off to FY79.

Interfaces

Significant interfaces exist between this element on exploitation strategies and all other program elements. Most other elements provide information on forecasting outcomes of choices in the decision making process of any strategy. The element on economics provides perhaps the most important measure of the value of any strategy. Improved, more reliable procedures for assuring the outcome of an exploitation strategy make this program element the most important practical part of the entire geothermal reservoir engineering research program.

TABLE V-1

EXPLOITATION STRATEGIES

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASK
Exploitation Strategies	1. Review and assessment of existent strategies.	a. Non-geothermal mineral industries.
		b. Geothermal.
	2. Development of new and alternative strategies.	a. Optimization with respect to business criteria, e.g. maximum profit, minimum investment, etc.
	3. Case studies.	

TABLE V-2

		FY '78													FY '79												
RESEARCH PROJECT	.	O	N	D	J	F	M	A	M	J	J	A	S	.	O	N	D	J	F	M	A	M	J	J	A	S	.
1.a. Review and assessment, non-geothermal											○	—	—	△	—	—	—	—	—	—	—	—	—	—	—	—	△
b. Review and assessment, geothermal											○	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	△
2.a. New and alternative strategies - business point of view											○	—	—	—	△	—	—	—	—	—	—	—	—	—	—	—	□
b. New and alternative strategies - other criteria											○	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	□
3. Case studies											○	—	—	—	—	△	—	—	—	—	—	—	—	—	—	—	□

Legend:

○—— Proposed start of project/task.

□—— Indefinite start of project/task.

——△ Anticipated report, project milestone, or termination.

——□ Indefinite milestone.

ELEMENT VI: ECONOMICS

Background

Economic evaluation of geothermal reservoirs should be able to answer the following questions: (1) What are the costs to establish a system for exploitation of the reservoir? (2) What is the value of established potential production? (3) What are the risks and uncertainties associated with forecasts of the economic value of anticipated production? The first two questions are concerned primarily with the more obvious costs of doing business: How much of an investment in wells, etc. is needed to exploit the reservoirs? What are the operating costs, such as maintenance, taxes, to produce the reservoir? What must be the selling price of the geothermal fuel to yield an acceptable return? At what rates of income production can the fuel be produced over the economic life of the reservoir? These questions, in a broad sense, must also be concerned with societal and environmental costs and benefits that stem from producing the reservoir.

The latter question is concerned with the same matters but from the risk standpoint: uncertainties in costs, prices, production rates, the life of the reservoir, and still other potential risks, e.g. downtime because of scale buildup on turbine blades, etc. All these risks may be the economic deterrents to reservoir development.

Geothermal reservoir economic evaluations are analogous in most respects to petroleum reservoir evaluations. Adequate analytical techniques for petroleum reservoir evaluations are available [1,2]. Good models [3,4,5,6] are available for analyzing surface energy conversion technologies and estimating the hypothetical competitive value of geothermal energy for both electrical and non-electrical uses. These models require reservoir engineering data, well flow and decline curves, as input, in order to determine value based on costs. Economic models which combine reservoir mechanics and end use technologies within a single systematic framework are, unfortunately, lacking.

The valuation of geothermal reservoirs can be viewed from many standpoints; e.g., asset value, revenue potential, rate of return on investment, fair market value, and value as a substitute for other energy sources. The economic emphasis in this element is on the optimum use of this resource. However, emphasis in other elements (except "Exploitation Strategies") is on the description of resources and the phenomenology of their producing mechanisms. All these concepts come together, however, in life cycle economic analyses using discounted cash flow techniques. The literature is rich [7,8,9] in both descriptions and examples of techniques suitable for life cycle economic modeling. The concepts underlying these models should be applicable to economic models for geothermal reservoirs and, in fact, some have already been set up [3,5,6].

Statement of the Problem

Economics plays a critical role in the geothermal development process. For the developer, justification of an exploration program and of an exploitation program depends upon an assessment of the economic value of a geothermal reservoir. Economic value is based on the potential of the reservoir under a particular development strategy. Determination of the economic value is complex and involves consideration of reservoir, energy conversion technology, and life cycle costing parameters. It also involves substantial risk inasmuch as assessments must be made from limited data.

Confidence in the economic evaluation of a geothermal reservoir depends upon the level of uncertainties associated with such parameters as useful life, productivity, etc., and also on the reliability of the energy conversion system used in connection with its exploitation. Currently, a methodology is not generally available for determining the level of economic risk associated with uncertainties in all these parameters. There is clearly a need for determination of appropriate economic risks and for introduction of this information into economic models.

Environmental, legal, regulatory, and other institutional and societal factors may impose limitations to potential exploitation strategies. To the extent possible, economic evaluations need to consider these factors and identify associated development constraints as they relate to economic assessment.

Discussion of the Solution

Several economic models have been developed to assess reservoir value in the petroleum industry [1,2]. The merits of these existing models need to be evaluated as they relate to geothermal reservoir assessment and risk analysis. Once deficiencies in existing models are determined, requirements for improved or next generation models can be specified.

It is anticipated that models will be developed to combine forecasts of reservoir performance and surface energy conversion technology within a single systematic framework. Such a model would assist the developer in assessing the life cycle value of a project. Risk assessment methods need to be developed. Such methods will need to consider the accuracy and precision of resource assessment measurements, the uncertainties in the interpretation of resource assessment data, and the uncertainties in predicted reservoir performance.

Research Objectives

Research objectives include:

- Assess the merits of existing economic evaluation methods and models as they relate to geothermal reservoir development.
- Develop an improved economic evaluation assessment capability combining reservoir mechanics and surface energy conversion technology into a single framework.
- Develop a capability for consideration of measurement accuracy and precision as well as uncertainties in interpretation of data and predictions of reservoir performance as they relate to

Discussion of Research Projects

The projects currently conceived under this element of research are presented in Table V-1. Several comments on this table are called for.

There is a need for what might be termed a definitive assessment of economic models for other mineral industries in order to determine fully the extent to which concepts used therein are applicable to geothermal resources. Some effort along these lines has already been done [3,4].

The need for an integrated life cycle economic model has already been emphasized. Perhaps the most difficult aspect of this effort will be in appreciating methods for introducing the possibility of temperature decline during the production of the resource. As such it is recognized as a special task.

Inasmuch as there can be several scenarios for exploitation of a geothermal resource, each of which may have a different economic value, the notion of optimization is mentioned in the Table. This effort is also covered, as might be expected, in the section "Exploitation Strategies."

Risk and risk analysis is a major feature of all resource exploitation inasmuch as decisions are always being made with limited data. There is a need to list the parameters that affect economic analyses and then to determine the experience base for assigning average values and boundaries to these parameters. There is also a need to evaluate methods for improving methods for determining these parameters for specific cases. For instance, should additional wells be drilled and tested prior to committing to construction of a 15MW power plant? A 55MW power plant?, etc. The whole concept of risk must then be introduced into integrated life cycle economic models for geothermal resources.

Research Schedule and Results

A proposed schedule for implementation of this element of research is presented in Table V-2. The schedule calls for assessment of available economic models and evaluation of risk parameters by the end of FY78. A level of effort program should be started in FY78 for work on developing an integrated life cycle economic model and on the question of optimization. Work involving temperature declines as a part of economic models should be put off to FY79 inasmuch as there will most likely be no data on temperature declines in geothermal reservoirs until then. Likewise, work on the introduction of risk into economic models should be put off until FY79 when, presumably, data on risk becomes available.

Interfaces

This program element interfaces with the element on Exploitation Strategies very closely. Also it is highly dependent on modeling inasmuch as modeling provides the basis for forecasting production of the salable commodity, namely geothermal fuel. Data on risk are expected to be derived from the element on site specific studies; and, indirectly on all time elements on which site specific studies depend, e.g. well testing, borehole geophysics, etc.

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TABLE VI-1

DESCRIPTION OF RESEARCH IN ECONOMICS OF GEOTHERMAL RESOURCES

RESEARCH CATEGORY	RESEARCH PROJECT	RESEARCH TASKS
Economics	1. Assess existing economic evaluation methods from other mineral industries.	
	2. Develop integrated life cycle economic model for geothermal resource development.	a. Integrate resource evaluation model with model for economics for surface energy conversion systems. b. Optimization studies. (See also section on "Exploitation Strategies.")
	3. Risk analysis as a part of integrated life cycle economic model.	a. Evaluate values of risk parameters; e.g. experience base for estimates of decline functions, etc. b. Introduce risk analysis into integrated life cycle economic model.
	4. Comparative economics with alternate energy sources.	

TABLE VI-2

		FY '78													FY '79												
SUGGESTED RESEARCH TASK	.	O	N	D	J	F	M	A	M	J	J	A	S	.	O	N	D	J	F	M	A	M	J	J	A	S	.
1. Assessment of existent economic models.											○	—	—	△													
2.a. Develop integrated life cycle economic model.														○	—	—	—	—	—	—	—	—	—	—	—	—	△
b. Optimization studies.														○	—	—	—	—	—	—	—	—	—	—	—	—	△
3.a. Evaluation of risk parameters.														○	—	—	—	—	—	—	—	—	—	—	—	—	□
b. Introduction of risk analysis into economic models.														○	—	—	—	—	—	—	—	—	—	—	—	—	△
4. Comparative economics with alternate energy sources.											○	—	—	△	—	—	—	—	—	—	—	—	—	—	—	—	□

Legend:

○——— Proposed start of project/task.

□——— Indefinite start of project/task.

———△ Anticipated report, project milestone, or termination.

———□ Indefinite milestone.

APPENDIX B

COMMENTS ON THE RESEARCH ELEMENTS BY THE REVIEW TASK FORCE

The report of the moderator of the Review Task Force is presented here. It expresses the opinions of the Task Force regarding the objectives of the GREMP research elements, and the assigning of research priorities.

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DR. JAMES H. BARKMAN
VICE PRESIDENT - PRODUCTION

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August 31, 1977

Dr. J. H. Howard
Head - ERDA/DGE
Reservoir Engineering Management
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Subject: Reservoir Engineering Management Program (REMP): Comments by The Review Task Force

Dear Dr. Howard:

The Review Task Force met on August 4 and 5, 1977 to review the draft REMP document. The purpose of this letter is to express our thoughts regarding (1) the completeness of the document and (2) the priorities that should be assigned to the categories of research that make up the document.

The Task Force identified a number of areas of research that were omitted or given insufficient attention in the draft document. Progress in these areas is believed to be necessary in order to meet our goals for geothermal resource development. These include: well stimulation, scale prevention, downhole well pumping, two-phase vertical flow in wellbores, induced seismicity, and studies of natural fracture systems. (Note the individual letter from J. C. Martin.) Some of these topics may be implicit in the program; however, we feel that they are high priority items and should be more clearly identified.

As expected with a group of diverse backgrounds and interests, a unanimous opinion on priorities was not reached. Nevertheless, we feel satisfied that our assignment of priorities to the various parts of the program reflects a reasonable consensus as to where ERDA/DGE and LBL should place their priorities during the coming fiscal year.

In considering the merit of various projects, we were aware that some work is already funded and under way. Furthermore, we recognized that there is potential overlap with other programs such as the Subsidence Program. Our rankings and comments reflect the total effort that we feel should be devoted to the different categories of research in REMP regardless of where and under what program the work is done.

The Task Force feels strongly that the Well Logging Project should not be separated from the REMP at this time. Interpretive well logging and reservoir engineering should be closely coordinated. This approach does not prevent future implementation of the well logging element by whichever national laboratory can do the work most effectively.

The ranking of categories and elements of the proposed program by the Task Force is given in the attached table. In addition, a summary discussion of each element is attached. Each of these summaries represent either the consensus of the group, or if that was not possible, the majority opinion.

A few members of the Task Force stated that the program might better be called the Exploitation Engineering Management Program. The feeling was that this would more accurately reflect the scope of the program than the current title. We doubt that the change would be very significant, however.

The members of the Task Force appreciate the opportunity to take part in the formulation of REMP. We recommend early implementation of this program and hope that ERDA will support it to the fullest extent possible.

Members of the Task Force:

JHBarkman
J. H. Barkman, Moderator
G. B. Bodvarsson
W. E. Brigham
R. L. Christiansen
G. L. Frye
M. S. Gulati
P. N. La Mori
J. C. Martin
C. W. Morris
G. F. Pinder
H. J. Ramey

Attachments:
1. Table of Priorities
2. Comments on the elements and categories of the document
3. Letter by John Martin

TABLE OF PRIORITIES

RESERVOIR ENGINEERING MANAGEMENT PROGRAM

Priority Number	Element/Category		Priority Scale *
1	II.C.	Well testing	9.9
2	II.B.	Interpretive borehole geophysics	8.8
3	II.D.	Geochemical techniques and problems	7.6
3	I.	Properties of materials	7.6
4	IV.B.	Numerical modeling	7.4
5	III.B.	Site specific studies	6.3
6	III.A.	Fundamental studies	5.9
7	IV.A.	Analytical modeling	5.4
8	II.A.	Surface geophysics	3.9
9	IV.C.	Physical modeling	3.4
10	VI.	Economics	1.6
11	V.	Exploitation strategy	1.5

* On a scale of 0 - 10.

COMMENTS ON THE
ELEMENTS AND CATEGORIES OF REMP

I. Properties of Materials
II.A Surface Geophysics
II.B. Interpretive Wellbore Geophysics - Well Logging
II.C. Well Testing
II.D. Geochemical Techniques and Problems
III.A. Fundamental Studies
III.B. Site Specific Studies
IV.A. Analytical Modeling
IV.B. Numerical Modeling
IV.C. Physical Modeling
V. Exploitation Strategies
VI. Economics

I Properties of Materials

The Task Force recommends that the measurement of the thermal expansion and contraction of rock and rock compression characteristics be moved from Item 2 to Item 1 in Table 1, and that Item 1 be expanded to include porosity and the effects of fractures on permeability, porosity, etc. Rock samples should be subjected to various temperatures, pore pressures, and confining stresses, including unequal principal stresses. Both bulk compression and pore compression characteristics should be measured.

II.A. Surface Geophysics

The use of surface geophysical techniques to help define reservoir systems was ranked rather low by the committee for two basic reasons:

(1) generally useful results will require considerable time, and

(2) any technique that is likely to be useful in the short term in a specific reservoir will be known by the producers and used as economics and need dictate. An overall low level "state of knowledge" effort to keep abreast of the developments in the ERDA exploration geophysics program does seem worthwhile, but is presently going on anyway. Any further effort should be confined to tighter resolution as needed for reservoir descriptions.

II.B. Interpretive Wellbore Geophysics - Well Logging

The most important conclusions in this project are:

(1) It is basically wrong to separate this work from the rest of the reservoir engineering effort, and

(2) the element as a whole is highly important.

The interpretive effort in this work is so closely interrelated with the rest of the reservoir engineering effort, it requires close interaction with the other projects. There will be a continuing need for guidance of this project from results of others, and guidance of others from the results of the logging efforts.

The hardware development portion of this project is presently being well-handled at Sandia. Strong communication is required here as well to assure that the new hardware gets used.

The calibration well concept is a good one. In fact, it is a necessary adjunct to the interpretive research effort. Other necessary auxiliary efforts are: core information that can be related directly to log information, and the use of log data to improve surface geophysical interpretation. The importance of log interpretation in fractured systems has not been emphasized adequately.

The section on development of interpretive techniques has been stated in a rather cursory manner. This was surely due to the fact that a more thorough statement would require many more pages in an already long document. However, a few more definitive task statements would be useful.

II.C. Well Testing

Well testing usually involves several different periods in development of a geothermal resource, and several different purposes. This has caused this subject to appear under several categories in the REMP. For example, well testing is done both during drilling to permit a decision on well completion (drilling stem testing) and later, after a permanent completion. Drill stem testing is often considered a drilling procedure. After completion, objectives of testing include determination of well condition, formation conductivity (permeability-thickness) and driving force for production (mean formation pressure). However, consideration of flow in the wellbore, pumps, flow metering at the surface and downhole, and flow through a gathering system on the surface often fall into the province of the production and/or reservoir engineer who conducts a well test. Almost all of these activities need attention for speedy geothermal development.

This category was considered the most important to the REMP. It is a broad category that includes development of tools, instruments, testing procedures, drill-stem-testing methods and analyses, and new testing procedures and interpretative methods.

In regard to instruments, it was found that Sandia laboratories has a program in progress that appears to have achieved most objectives for increased temperature level tolerance for temperature and pressure measurement. However, there is important need for pressure instruments whose calibrations are not strongly temperature-sensitive. The committee recommends that the Sandia group report to the LBL REMP.

Another related effort is development of reliable multiphase flow metering and computational methods for flow in vertical and horizontal pipe, and inclined pipe. Much pertinent work exists which should be integrated into this study.

It was concluded that development of high rate downhole pumps is also important to this effort. The general feeling in the geothermal industry is that many if not all wells will benefit by pumping. The only pump available that is considered reliable is the shaft-driven type. Considerable room for improvement in reliability and efficiency exists. Other types of pumps such as the downhole turbine or the electric submersible should be developed.

Another area mentioned was development of reliable high-temperature drill-stem-test equipment and interpretative methods.

A large area of importance is development of new interpretative models appropriate for geothermal systems. Such factors as fractures, high velocity flow (non-Darcy flow) and reduction of permeability due to boiling require study.

II.D. Geochemical Techniques and Problems

The general feeling was that Table 1 needs some changes. Project 1 needs to be restated in more specific terms to avoid the impression that this is only a literature search, or combine this with Project 2. Rename Project 2 "Investigation of the Geochemistry." Add to Project 2 the task of investigating phase behavior of dissolved gases such as CO_2, H_2S, etc., in geothermal brines. Project 3 should include tasks on corrosion and scale problems. Remove Project 4 from this element.

It might be worth stating that the geochemistry of geothermal systems should include nonequilibrium conditions in all the tasks. This might be included in the element description. The application of tracers to the study of geothermal reservoirs should be highlighted.

This element is considered to be important to the objective stated by ERDA with funding of the element to be relatively high.

III.A. Fundamental Studies

The group feels that this element is important as a catchall to allow unsolicited proposals on relevant geothermal topics. It should be included but <u>not</u> have an RFP put out. This element allows for the consideration of tasks not specifically named or considered in other elements. It is necessary because we cannot expect to know or anticipate all research tasks in this field.

III.B. Site Specific Studies

The Review Task Force expressed support for this subelement when applied to field cases currently under production, i.e., Larderello, Cerro Prieto and various Japanese fields. In fact, some members felt that this subelement should be relabeled "Field Case Histories." Synthesis and generalization of a prototype field is more appropriate under subelement III.A.(conceptualization of a geothermal resource).

IV.A. Analytical Modeling

The Task Force agreed in principle with the proposed task formulation. It was suggested that the principle emphasis should be directed toward analytical solutions which could be utilized to demonstrate the accuracy of numerical simulators. The last project, other demonstrably useful analytical problems, should be omitted.

IV.B. Numerical Modeling

The Task Force felt that a comparison of existing numerical simulators should be undertaken at an early date. There was a general consensus that separating subsidence from this task was conceptually and physically unreasonable. The inclusion of fractures as an integral part of a geothermal simulator seems warranted. The use of the word phenomenology is inappropriate.

IV.C. Physical Modeling

The examination of the theoretical foundation of scale models of geothermal reservoirs appears needed. While experiments designed as a basis for numerical simulation or to expose the fundamental laws governing geothermal reservoir physics appear warranted, physical models of field problems would not likely prove cost effective.

V. Exploitation Strategies

The industrial members of the Review Task Force unanimously agreed that this element of the REMP was of uncertain value and not recommended for funding. To fund this element would dilute ERDA's effort in the far more important elements in terms of achieving ERDA's goals. Only two of the academic members assigned some value to this element. If other planning and regulatory agencies of government (i.e., Conservation Division, USGS) required research in this element, then they should fund the research directly.

VI. Economics

All of the industrial members of the Review Task Force stated that their individual companies would develop their own economic models regardless of ERDA funding efforts. This viewpoint was supported by the academic member who had had previous extensive industrial experience. Although not stated as a research objective in the element, some moderate level of support was expressed for studies of alternative energy cost comparisons. These comparisons could be useful to both the exploitation companies and to the utilities and thereby help achieve the mission of the Division of Geothermal Energy.

Chevron

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August 10, 1977

TWO ADDITIONAL
GEOTHERMAL RESEARCH CATEGORIES

Mr. J. H. Howard
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Mr. J. H. Barkman
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Dear Messrs. Howard and Barkman:

There are two possible additional research categories, well performance and geomechanics, that I feel warrant consideration for inclusion in ERDA's geothermal research program. Parts of both categories are already included in the proposed program. Unfortunately, other parts seem to have been omitted.

The well performance category should include all aspects of well behavior not adequately covered in other categories. This new category should include well bore hydraulics, drilling and well completion except the rock mechanics aspects, downhole equipment and instrumentation except well logging tools, downhole corrosion and scale, and well damage and stimulation. Geomechanics should include all aspects of earth stress-strain-failure behavior, including the subsidence research program, the rock mechanics aspects of drilling, and natural and induced faults and fractures including hydraulic fracturing and induced seismicity.

Some of the subjects listed in the preceding paragraph are not commonly classified as reservoir engineering. However, as brought out in our meeting last week, all aspects of exploitation engineering are related, and I am sure we all want ERDA to have a comprehensive, well-balanced geothermal research program. The inclusion of the two additional categories will go a long way toward rounding out the program.

Sincerely,

J. C. Martin

J. C. Martin
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