Title

AN UPDATED PLAN FOR SUPPORT OF RESEARCH RELATED TO GEOTHERMAL RESERVOIR ENGINEERING

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AN UPDATED PLAN FOR SUPPORT OF RESEARCH RELATED TO GEOTHERMAL RESERVOIR ENGINEERING

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DISCLAIMER

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INTRODUCTION

Background

Several years have passed since the original plan for support of research in geothermal reservoir engineering, or "GREMP" as the plan was called, was issued (Lawrence Berkeley Laboratory, 1977). The plan has been implemented to a degree governed by the prioritized research elements, DOE Policy, the plan and by the availability of budgets and qualified manpower to conduct research. Since preparation of the original plan numerous developments in the federal geothermal program and in the geothermal industry have occurred which bear upon the plan. There is also now a record of activity for the program itself. In view of these changes and activities, it seems timely to review the original plan, to update it and to make it appropriate to those needs seen more clearly today. Such an update is the principal purpose of this document.

The original plan benefited a great deal from the advice and guidance of the original Industry Review Task Force. Likewise, this plan has had the benefit of a Review Task Force, of a special solicitation of industry opinion (Schwartz and Klock, 1979) and of three years of interaction with the geothermal community as a whole.

As a basis for an updated plan, we compare the original plan with accomplishments to date. Comparison provides the basis for a new plan, but the new plan is <u>not</u> simply the difference between the original plan and the accomplishments. Also included are recommendations on the new priorities that should be assigned to various categories of work and, furthermore, recognition of one new general area of work.

Research in petroleum reservoir engineering dates back more than 50 years, but DOE/DGE support of geothermal reservoir engineering research has been underway since only 1977. While certain accomplishments have been made in the geothermal program, it should be appreciated that some activities have only begun. An example is the evaluation of tracers in geothermal reservoirs. The new plan recognizes the need for continued support of work on important activities that have just started.

Goals and Objectives

The primary goal of the U.S. Department of Energy (DOE)/Division of Geothermal Energy's (DGE), Geothermal Reservoir Engineering Management Program (GREMP) is to accelerate development and exploitation of geothermal resources through identification and elimination of technical obstacles.

The GREMP goal stated above is one of DOE/DGE's (ERDA-86) responses to goals set forth in the "National Geothermal Program for Resource Inventory and Assessment and for Research and Development" mandated in Public Law 93-410 in Sec. 103 and 104, respectively. These specific national program goals include:

- "Improvement of geophysical, geochemical, geological, and hydrological techniques necessary for locating and evaluating geothermal resources."
- "Development of better methods for predicting the power potential and longevity of geothermal reservoirs."
- "Determination and assessment of the nature and power potential of the deeper unexplored parts of high temperature geothermal convection systems."

- "Survey and assessment of regional and national geothermal resources of all types."
- "Research to develop, improve, and test technologies for the discovery and evaluation of all forms of geothermal resources..."
- "...research into the principles controlling the location, occurrences, size, temperature, energy content, producibility, and economic lifetimes of geothermal reservoirs."
- "Research and development...for the purpose of resolving all major technical problems inhibiting the fullest possible commercial utilization of geothermal resources in the United States."
- Provision "for an adequate supply of scientists to perform required geothermal research and development activities."

The GREMP program is supported by DOE/DGE, through Lawrence Berkeley Laboratory, and consists of research projects conducted by the Geothermal Group, Earth Sciences Division /LBL, and by various subcontractors to LBL. The general objectives of the GREMP program are:

- To define and promote resolution of technical and scientific reservoir engineering problems (as described in PL 93-410) impeding the development and exploitation of geothermal reservoirs.
- To assist in establishing a cohesive geothermal reservoir engineering community composed of engineers from industry, universities, and government laboratories.
- To assist the education and training of personnel who can staff this community in the future.
- Technology transfer - especially case studies for geothermal rules-of-thumb, and site-specific applications for developer, operator, and investor confidence.

COMPARISON OF ORIGINAL PLAN WITH ACCOMPLISHMENTS SINCE 1977

Status of the Current Research

The broad outline of geothermal reservoir engineering-related research in terms of the eleven original research categories is shown in Figure 1. The numbered boxes refer to the research categories initially identified in LBL-7000 (1977). The boxes with dashed outlines were later removed from GREMP by DOE/DGE.

Properties of materials investigations and data tabulations are being conducted, principally by TerraTek, Inc., Salt Lake City, who receive separate funding from DOE/DGE to determine properties of available cores from geothermal reservoirs: electrical conductivity, acoustic velocity, compressibility, thermal expansion, porosity, permeability, thermal conductivity, thermal diffusivity. In addition, TerraTek receives support for creep testing from LBL through the DOE/DGE Geothermal Subsidence Research Program.

Surface Geophysics was merged into the Geothermal Exploration Technology Program managed by the Earth Science Laboratory (ESL) of the University of Utah Research Institute (UURI) and DOE/IDO. However, through its in-house reservoir engineering program, LBL maintains some elements of surface geophysics for reservoir monitoring at the Cerro Prieto Geothermal Field.

Well Log Interpretation was elevated to separate research program status and is now managed by LASL.

Well Log Instrumentation, never intended to be a part of the GREMP research, continues to be managed by Sandia Laboratories, and is concerned

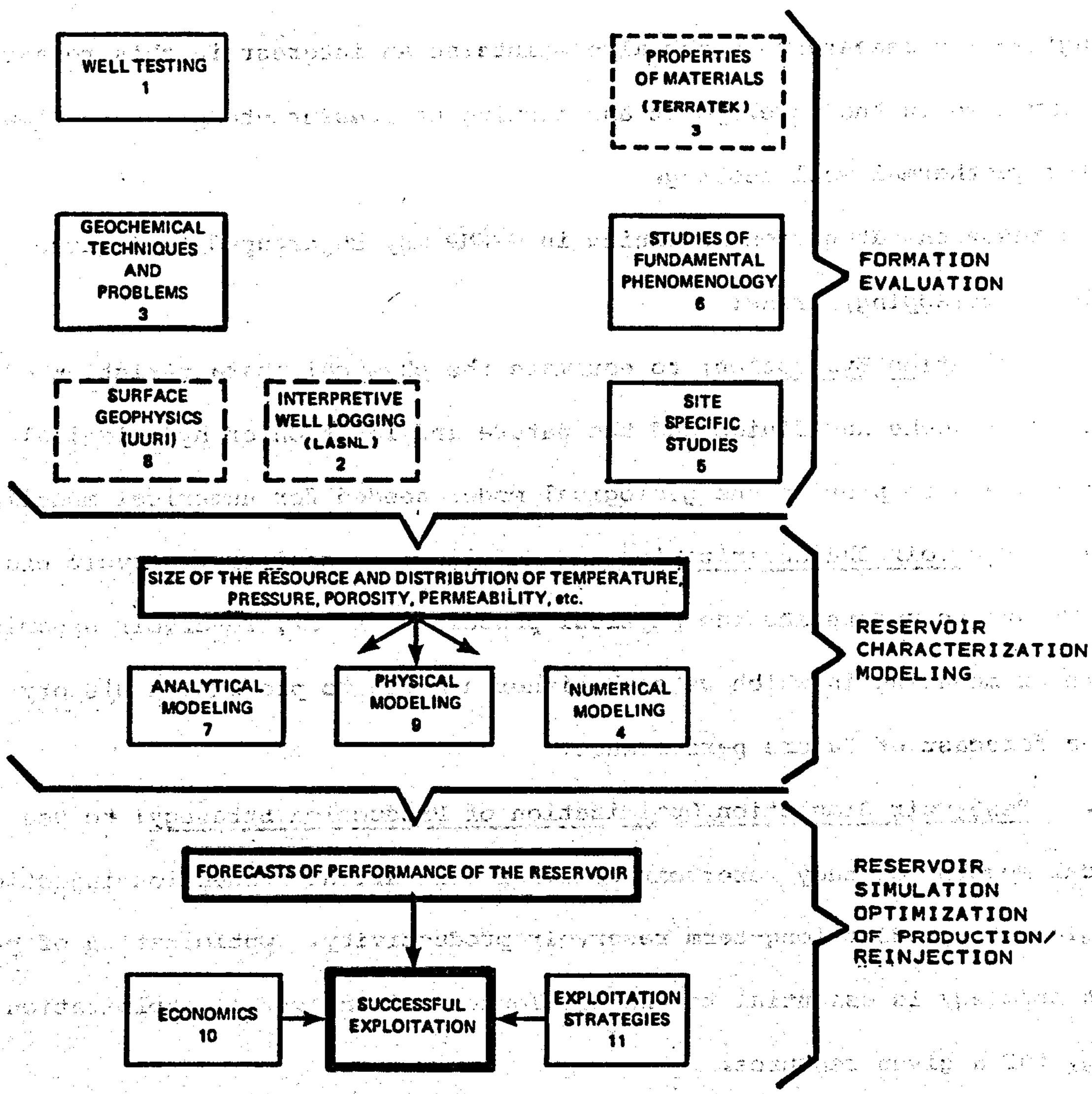

Figure 1. Elements of the original GREMP Plan. (Note: Small number in research area box indicates relative priority with respect to other research areas.)

mainly with the development and/or testing of electronic components, seals and cables for high temperature and corrosive environments. LBL's in-house reservoir engineering research program also maintains an interest in this research. LBL is involved in the development and testing of pressure-temperature-flow tools for geothermal well testing.

The research categories remaining in GREMP may be grouped into three main, but overlapping, areas:

1. Formation Evaluation; to estimate the physical characteristics of the reservoir rocks and fluids and the nature and location of hydrological boundaries; and to provide the geological model needed for numerical modeling.

2. Reservoir Characterization and Modeling; to confirm reservoir characteristics and to understand the physical processes (i. e., reservoir dynamics) by means of modeling in which we seek either a match to production history and/or a forecast of future performance.

3. Reservoir Simulation/Optimization of Production Strategy; to use numerical models to study reservoir behavior for various production-injection strategies, to predict long-term reservoir productivity. Optimization of production strategy is essential to the development of an overall exploitation strategy for a given resource.

Figures 2, 3, and 4, and Table 1 summarize the status of research accomplished through the DOE/DGE Geothermal Reservoir Engineering program.

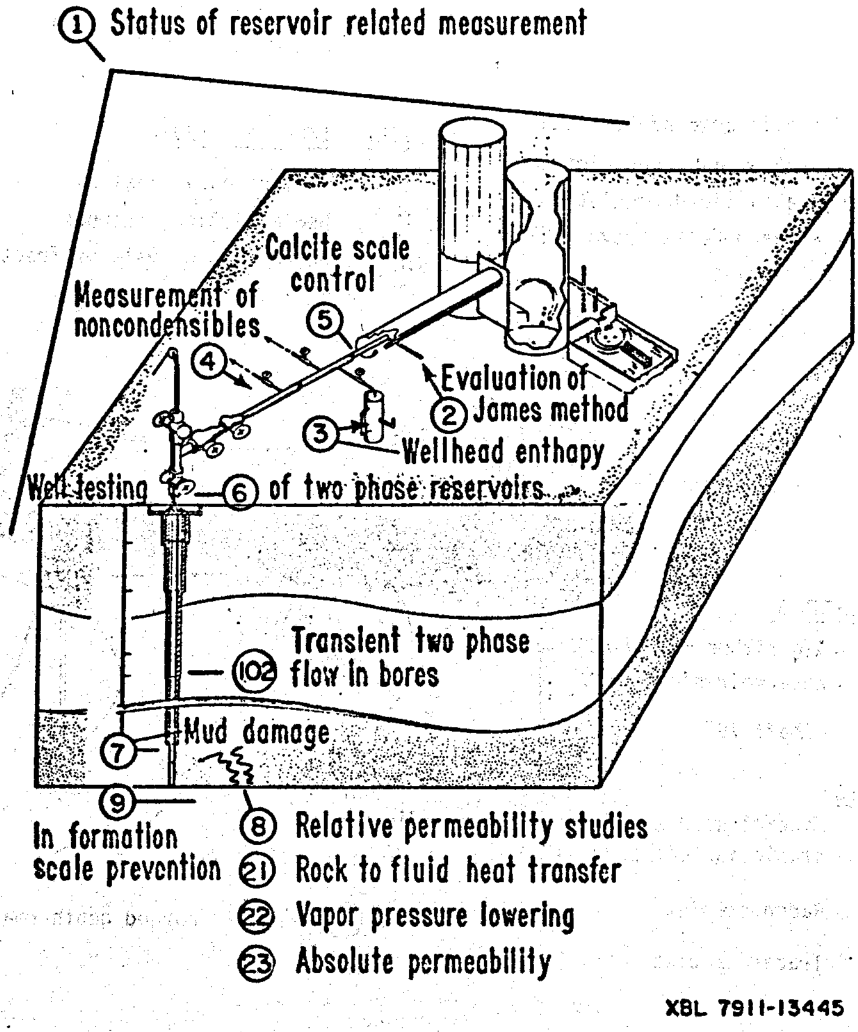

Figure 2. Summary diagram of well system and near-bore research projects.

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101 Numerical analysis of fractured well tests

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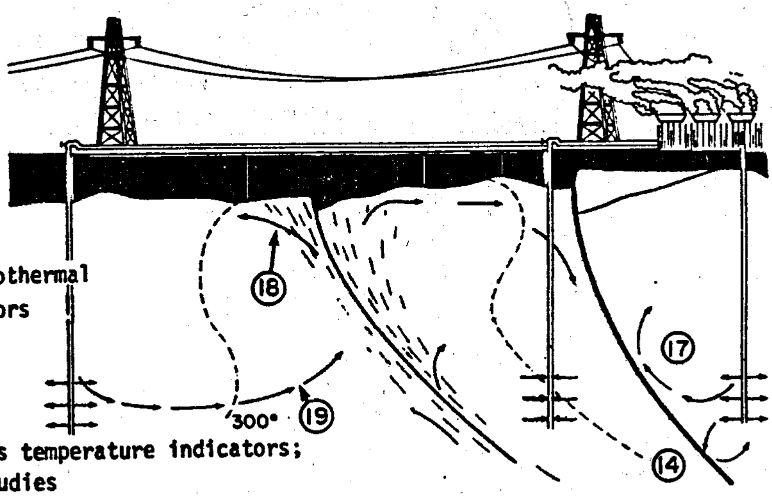

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103 "Shaft 79"

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17 Mineral studies as temperature indicators; stable isotope studies

18 Radon studies

19 Tracer studies

14 Fault charged geothermal reservoir

Figure 3. Summary diagram of mainly field-wide research projects (see Table 1). (XBL 7911-13444)

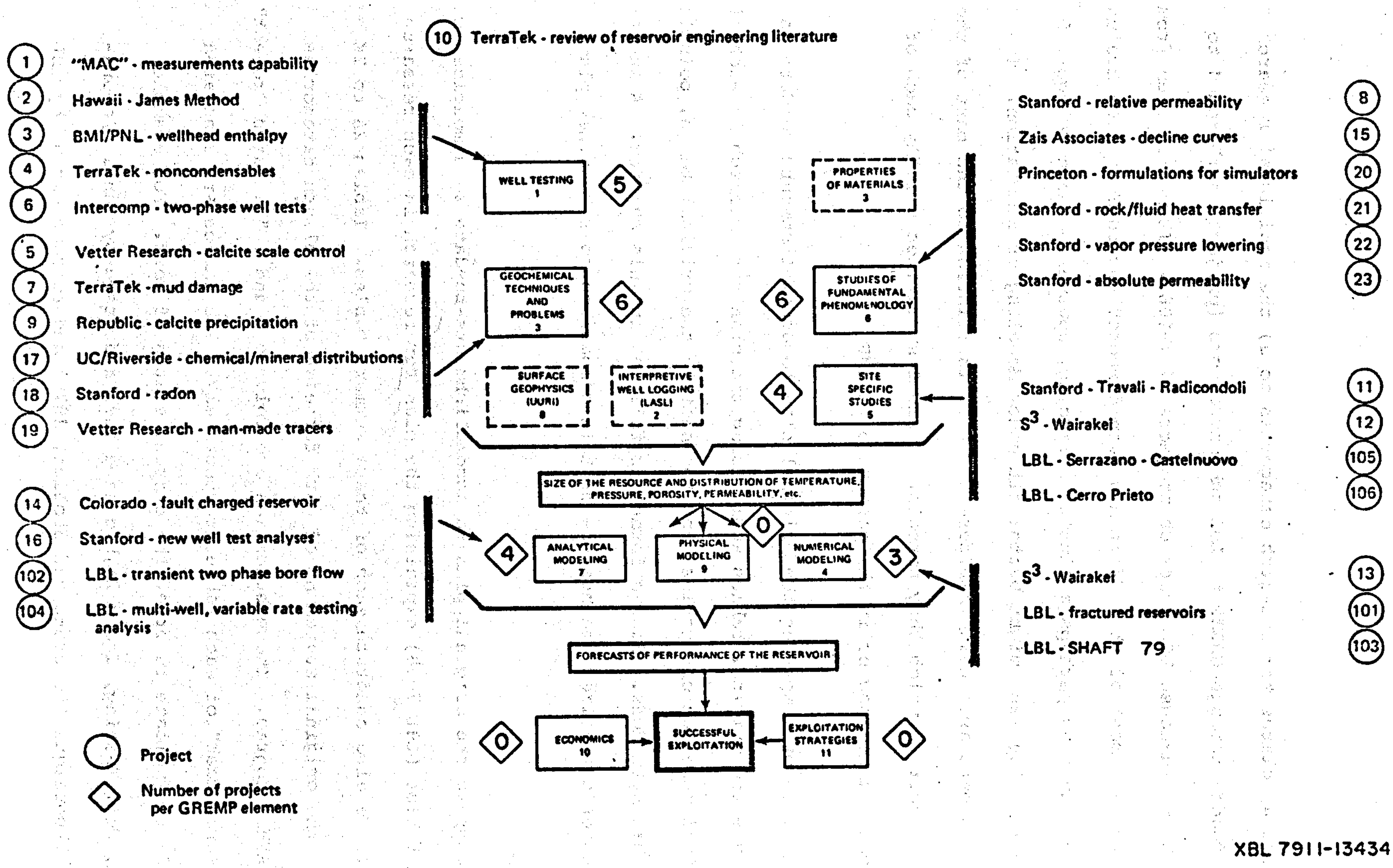

Figure 4. Summary of projects with respect to elements of original GREMP plan. (Small number in area box indicates relative priority with respect to other research areas.

Figure 4 relates the research categories to a) the individual research projects funded through GREMP to LBL subcontractors (projects numbered 1 to 23), and b) to in-house LBL research projects (101-106). It may be seen from this figure that most of the effort has been directed toward Formation Evaluation. The figure is perhaps a little misleading, however because Category 5, "Site Specific Studies" might better fit under Modeling or Simulation. The research projects are shown in Figures 2 and 3 in relation to the part of the entire reservoir to which they pertain. Table I summarizes briefly each of the projects funded now or in the past under GREMP.

One method of comparing the original plan to accomplishments to date is to reproduce the original tables summarizing the plan for research in each of the original research categories, and to annotate the original table, pointing out what has been done. Such a format is followed in this chapter. A subsequent chapter summarizes the essence of this comparison to form a new plan.

Comparison

To compare the original plan to accomplishments-to-date we summarize the original tables (LBL 7000) explaining the plan for research in each research category. We also annotate each of these summary tables. Tables 2A to 2K summarize the original statement of work for each of the eleven categories of the GREMP program. These summaries are Columns 1 and 2 "Research Project" and "Research Task" of each table, respectively. The tables are annotated (Column 3) to indicate in brief the current status of work. For example, Table 2A, Well Testing, Items 2a,b,c have been addressed by Sandia Laboratories, Albuquerque (Veneruso and Stoller, 1979) and to some extent by LBL.

The various tables (2A - 2K) are arranged in descending order of original priority beginning with "Well Testing", the category given highest priority by the Review Task Force for the original plan.

COMMENTARY ON THE COMPARISON AND AN UPDATED PLAN

Review of Tables 1 and 2A to 2K shows that many recognized research needs have been addressed, some have not been addressed, and many have begun but are not yet fully completed.

LBL, collectively, has reviewed the status of research in reservoir engineering, and, in view of:

- activities supported and completed,
- activities underway,
- comments offered by industry (see particularly the report by Schwarz and Klock, 1979), and
- LBL overall expertise.

LBL has prepared still another table which summarizes these comparisons and offers an opinion as to priority, level of effort, and duration for additional effort. It is impossible to detail every argument concerning the priority, level of effort, and duration for each activity listed in Table 3. Indeed, to some extent, it is subjective; and others may assign things differently. Nevertheless, if one accepts the conclusions of Table 3, one can, in turn, prepare a summarizing table of the highest priority items. Table 4 presents this summary, and lists a budget for FY 81, 82, and 83 at estimated minimum total costs of $2500, 2610, and 2660 kilodollars, respectively. In comparison, the budget for FY 81 for a program including items of the first three categories of priority (namely priority Categories A, B, and C) is $3575 K.

Table 4 calls for effort in:

1. well testing instrumentation and practical analysis
2. geochemical techniques and problems
3. elucidation of the physical processes that operate in geothermal reservoirs and the determination and evaluation of parameters that characterize them, particularly boiling and relative permeability.
4. numerical modeling and applications of modeling to hypothetical field examples
5. field case histories including synthesis and generalization of these examples
6. some analytical modeling
7. economics and risk analysis (risk analysis is a new area of work).

The plan described by the table differs from the earlier plan in (a) being narrower in scope and more specific, (b) its emphasis on field studies, and (c) its higher priority on economics and risk analysis.

JUSTIFICATION OF THE UPDATED PLAN

Three principal concerns underlie justification for Table 4 and these are consistent with DOE/DGE policy, objectives, and goals. These concerns are:

1. To address and to solve technical and scientific problems that are clearly recognized as significant impediments to successful exploitation of geothermal resources. One example of such an impediment is the lack of good data on relative permeability of two phase flow through porous and fractured rock.

2. To demonstrate to developers, lending institutions, and utilities that geothermal reservoir engineers can indeed plan and execute successful development of geothermal reservoirs. Lack of credibility, of established track record is abstract but quite real and significant, and a major deterrent to investment in development in geothermal energy.

3. To clarify the economics and risks for geothermal resource development.

Marked with an asterisk on Table 4 are those research needs which address technical impediments. Those marked with a cross refer to needs that relate to concern over confidence in the credibility of geothermal reservoir engineering practice. A double asterisk refers to the economics or risk-related need.

Concern over removal of top-priority technical and scientific impediments requires no special comment assuming that one accepts the list of such impediments.

Concern over credibility of geothermal reservoir engineering practice should not be construed as a reflection on geothermal reservoir engineers but rather as a reflection of the status of geothermal resource industry. There is inadequate background whereby investors can judge the correctness of conclusions by geothermal reservoir engineers. Accordingly, an effort should be made to allay this concern, particularly through demonstration of the capability of geothermal reservoir engineers in practical situations. For this reason, field case studies, code development and application, decline curves analysis, risk analysis, and statistics need greater emphasis than has been given to them thus far. Risk analysis and the statistics related thereto are now recognized as a new area of work.

A comprehensive solicitation of industry by LBL (Schwarz and Klock, 1979) clearly revealed concern over the uncertainty involved in resource assessment and reservoir performance prediction. An effort is needed to demonstate that geothermal reservoir engineers:

1. work from a sound theoretical basis,
2. can estimate the uncertainty of their conclusions,
3. can recommend procedures to define the uncertainty more exactly and, if possible, to reduce the uncertainty.

DOE/DGE has supported studies of the economics of geothermal resource development (Cassel et al., 1979; Bloomster, 1978; and others). Again judging from the report of Schwarz and Klock (1979) it would appear that still more effort on real examples is called for.

The plan offered in this report should be implemented in a manner that assures the education of persons for the geothermal industry and assures the viability of a geothermal reservoir engineering community. In implementing the plan, special consideration ought to be given to groups that have played a key role in this regard, universities and university-related laboratories, in particular.

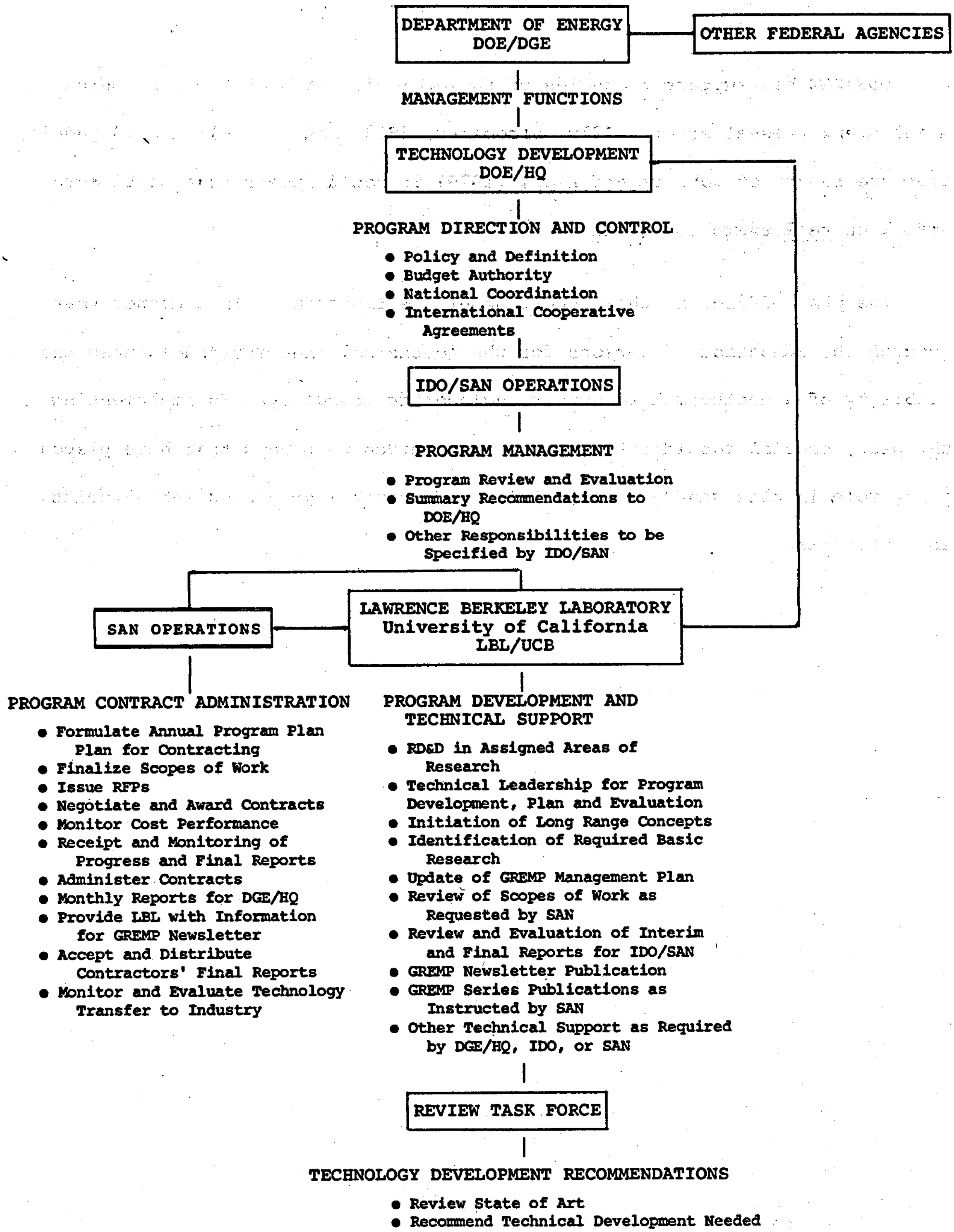

Figure 5. Management Plan

MANAGEMENT PLAN

Overview

A revised management structure for the Geothermal Reservoir Engineering Management Program, as shown in Figure 5, will be implemented beginning October 1, 1980. The changes reflect a transfer of responsibilities from LBL to DOE/SAN regarding the direct operation of the program. Efforts have been made to minimize overlap with other related DOE/DGE programs shown in Figure 6, and to encourage interface with programs concerned with resource types other than hydrothermal.

Program Direction and Control - DOE/DGE

The Manager, Geothermal Reservoir Engineering Technology, acting with concurrence of the Program Manager, Geothermal Technology Development with concurrence of the Director, Division of Geothermal Energy (DOE/DGE) will provide overall programmatic policy guidance for the definition, planning, direction and control of the Geothermal Reservoir Engineering Program. DOE/DGE will also provide overall budget authority to the DOE-supported participants in the program, including sub-program-level guidance to the Geothermal Program at the Idaho and San Francisco Operations' Offices. The Manager for Geothermal Reservoir Engineering Technology will be responsible for the national coordination of this program with other national geothermal program elements contained within DOE, as shown in Figure 6, and with the USGS and other agencies participating in the national geothermal program. Initiation and coordination of international agreements are the responsibility of the DOE/DGE Headquarters.

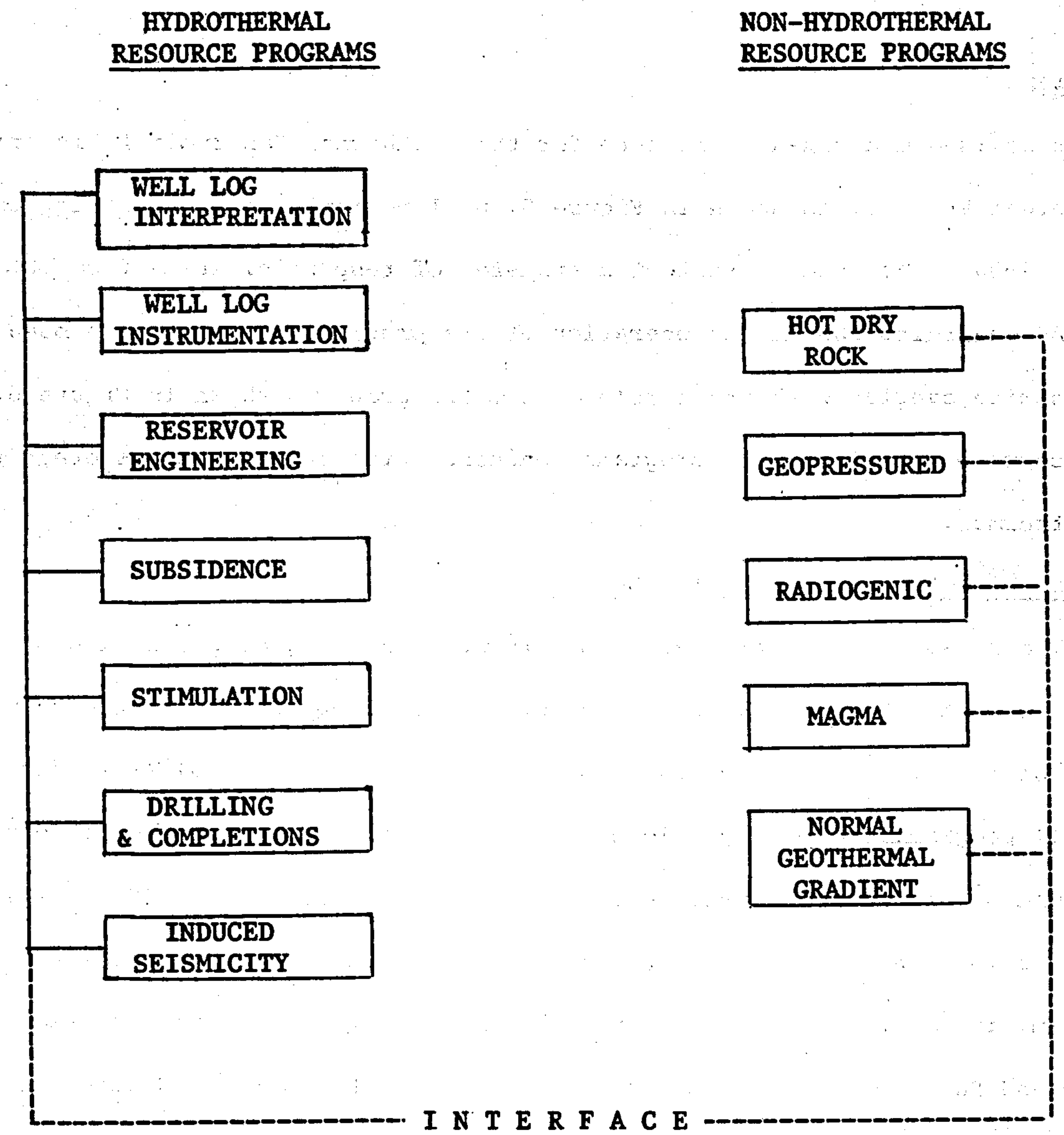

Figure 6. National Geothermal Programs contained within DOE.

Program Management - Operations Offices, San Francisco (DOE/SAN) and Idaho (DOE/IDO)

The Office of Geothermal Energy, Operations Offices in San Francisco and Idaho will provide program management including program review, evaluation, summary recommendations to DOE/DGE Headquarters, and other responsibilities to be specified by IDO/SAN.

Program Development and Technical Support - LBL

LBL/UCB will provide administrative and technical support for reservoir engineering and assessment technology. In detail, LBL/UCB will: perform RD&D in research areas assigned to LBL; provide technical leadership for program development, plans and evolution; initiate long range concepts; identify required basic research through discussion with and recommendations from the Review Task Force; synthesize comments on program direction and priorities; maintain general program communication, arrange and coordinate advisory committee meetings; update, as appropriate, the GREMP Management Plan based on input from government, industry, and academic sources; review and comment on scopes of work as requested by SAN; review/evaluate contractors' interim and final reports for IDO/SAN; produce the Geothermal Reservoir Engineering Management Program Newsletter (LBL Pub-332) based on information received from SAN; maintain a current Geothermal Reservoir Engineering mailing list; print and distribute new issues for the GREMP Series publications as instructed by DOE/DGE and SAN; and provide other technical support, as required by DGE, IDO, or SAN in keeping with budgets given to LBL for such support.

Program Contract Administration - SAN

The Office of Geothermal Energy, SAN Operations Office, will provide program contract administration, a responsibility formerly held by LBL. DOE/SAN will issue and review RFPs; formulate annual plan for contracting; negotiate and award contracts; and monitor cost performance. They will also be the monitoring entity responsible for the technical progress of contracts through interim and final reports. DOE/SAN will provide DGE/HQ with monthly technical progress and contract management reports; provide LBL with information (draft text, illustrations) for the GREMP Newsletter; accept and distribute contractors' final reports; and monitor and evaluate technology transfer to industry.

TABLES

Table 1. Summary of Geothermal Reservoir Engineering projects supported by USDOE/DGE through Lawrence Berkeley Laboratory.

ID#	Brief project name	Contractor	Brief summary of work
1.	Status of reservoir related measurements*	Measurement Analysis Corp.	A comprehensive appraisal of measurement needs and instrumentation for geothermal applications has been completed, indicating that commercially available technology and instrumentation exists in principle for all wellhead and process plant measurement requirements, except two-phase flow (Lamers, 1979).
2.	Theoretical basis for James method	University of Hawaii	The purpose of this project is to understand the theoretical basis of James' empirical method for estimating mass flow and enthalpy (Cheng, 1979).
3.	Measurement of enthalpy at wellhead*	Battelle Pacific Northwest Laboratory	Several calorimetry methods for measuring geothermal wellhead enthalpies were reviewed. A mixing tee condenser was recommended for use when cooling water is available. When not, a multiphase tank was recommended. Work on engineering drawings of a sampling system and a mixing tee condenser (Cliff et al., 1979a) have been prepared (Cliff et al., 1979b).
4.	Measurements of noncondensible gases at wellhead	TerraTek	Engineering design construction and testing of a device with the capability to monitor noncondensible gas concentrations continuously in geothermal discharges has been completed (Harrison et al., 1979).
5.	Control of calcite precipitation by additives*	Vetter Research	Scale inhibitor tests performed at Republic Geothermal Inc., East Mesa wells have shown that Dequest can economically eliminate calcite precipitation in the discharge flow stream (Vetter, 1979).
6.	Analysis of well tests of two-phase reservoir*	Intercomp	Favorable comparison of Intercomp's proprietary geothermal wellbore and reservoir simulators with the experimental and numerical results from three other models has been completed. Data on two-phase well tests have been assembled for analysis (Aydelotte and Taylor, 1979) and the Hawaiian well HCP-4 has been studied.
7.	Formation damage of drilling mud	TerraTek	Laboratory simulation of drilling mud damage to geothermal reservoir rocks has been initiated. Parameters to be considered are pressure, temperature, reservoir fluid chemistry, mud composition, and time (Butters, 1979).
8.	Relative permeability of steam and water	Stanford University	Relative permeability data have been collected by Counsil (1978).
9.	Calcite formation by inappropriate production practices*	Republic Geothermal, Inc.	Carbonate-rich geothermal brine is being passed through containers of granular materials in order to evaluate the mechanism and rate of calcite precipitation within the pore space. The ultimate practical purpose of the activity is to plan better remedial "acid jobs" on calcite-fouled geothermal wells (Michaels, 1979).
10.	Literature review of reservoir exploitation*	TerraTek	An annotated bibliography covering reservoir modeling, exploitation strategies, and interpretation of production trends has been prepared (Harrison and Randall, 1979).
11.	Study of the Travali Radicondoli geothermal areas in Italy	Stanford University	Geology and pressure-production history of Serrazzano reservoir have been reviewed. Bottomhole temperatures and pressures have been calculated from wellhead measurements. Areal distribution of pressure has been mapped for seven different times spanning the last 15 years. A conceptual model of Travali Radicondoli geothermal field was developed on the basis of the available field data (Miller et al., 1978).
12.	Data collection for the Wairekei field, New Zealand*	Systems, Science and Software	All geological, geochemical, geophysical, and wellbore data from January, 1953 to December, 1976 has been collected and synthesized (Pritchett et al., 1978).
13.	Simulation of past and future performance at Wairakei, New Zealand	Systems, Science and Software	With the data collected and synthesized (#12 above), an attempt is under way to match the pressure and enthalpy and subsidence history during past production of the Wairakei field (Pritchett et al., 1979).
14.	Prototype of a fault-charged geothermal reservoir*	University of Colorado	A physical, viable, mathematical model of an unexploited geothermal system has been constructed in terms of a fault zone controlled charging of a reservoir (Kassoy and Goyal, 1979).

Table 1. Summary of Geothermal Reservoir Engineering projects supported by USDOE/DGE through Lawrence Berkeley Laboratory (continued).

ID#	Brief project name	Contractor	Brief summary of work
15.	Review of decline curves appropriate to geothermal reservoirs	E. Zais and Associates	The purpose of this project is to review decline curve procedures used in the petroleum industry, determine which procedures are applicable to geothermal systems, and establish a theoretical basis for applicability.
16.	New analytical well test methods for geothermal reservoirs	Stanford University	The utility of parallelipiped models has been investigated (Ramey et al., 1978).
17.	Studies of mineral facies and stable isotopes and their relations to geothermal reservoirs	University of California, Riverside	Cuttings and core samples, obtained from the six wells drilled during the year 1977 were studied and interpreted to define the current temperatures in the field (Elders et al., 1978).
18.	Understanding the significance of radon in geothermal reservoirs	Stanford University	The variation of radon associated with geothermal reservoir production has been analyzed and interpreted for several reservoirs throughout the world (Kruger et al., 1978).
19.	Studies of the use of tracers in geothermal reservoirs	Vetter Research	A program of literature review and laboratory evaluation of tracers suitable for use in geothermal reservoirs has been initiated.
20.	Study of basic formulation of simulators of geothermal reservoirs	Princeton University	Multiphase flow equations have been derived for a deformable porous medium. Equations for heat and mass transfer in a fractured reservoir have also been formulated. A computer code BIFEPS (Block Interactive Finite Element Processed Scheme) has been developed to solve nonlinear transient problems with one or two governing equations in two or three dimensions. (Pinder et al., 1978).
21.	Studies of heat transfer from rock to fluid	Stanford University	Heat flow from rock to water has been studied as a function of a number of parameters including the size of rock fragments (Kruger et al., 1979).
22.	Vapor pressure lowering phenomena of geothermal fluids	Stanford University	The project demonstrated that vapor pressure may be lowered as a consequence of a number of chemical and petrophysical parameters (F. Miller et al., 1980).
23.	Absolute permeability of geothermal fluids	Stanford University	The effects of temperature and chemical composition of the rock types on relative permeability has been investigated (F. Miller et al., 1980).
101.	Numerical analysis of well tests of fractured reservoirs	LBL	Analysis of fractured well responses during testing using numerical models has been studied. Results compare favorably with analytical solutions (Narasimhan and Palen, 1979).
102.	Transient two-phase flow in geothermal bores	LBL	A code simulating transient two-phase flow in bores has been written and compared against limited field data (C. W. Miller, 1979).
103.	Geothermal reservoir simulator SHAFT 78	LBL	A code to simulate mass and heat transport in porous media has been written and applied to hypothetical and real examples (Pruess et al., 1979).
104.	Multiple well, variable rate well test analysis	LBL	The ANALYZE code has been proven capable of this kind of analysis (McEdwards, 1979).
105.	Study of Serrazzano Castelnuevo geothermal area, Italy	LBL	SHAFT 79 is being used to reproduce past performance and forecast reinjection of liquid (Pruess et al., 1980).
106.	Study of the Cerro Prieto area, Mexico	LBL	A very comprehensive case study at Cerro Prieto is being carried out cooperatively with the Mexican government (Lippmann et al., 1978).

* Project completed.

Table 2-A. Well testing.

Research Project	Research Task	Annotation on original plan
1. Assess conditions in geothermal reservoirs that affect tool and analysis requirements.		1. Assessment of conditions that affect tool requirements done by Lamers (1979); significance of conditions in geothermal reservoirs that affect analysis are now more fully appreciated (e.g., appreciation of the consequences of nonisothermal regime in which a downhole pressure-sensing capillary tube is suspended (Miller and Haney, 1978).
2. Improved data gathering systems.	a. Develop improved pressure tool capable of 650°F, 0-5000 psi pressure, 0.01 accuracy, one second minimum readout interval b. Develop improved temperature tool capable of 650°F, accuracy of 1°F, continuous operating to 90 days. c. Develop reliable downhole flow meter for geothermal applications. d. Develop automated multiwell data gathering system.	2.a,b,c. Electronics hardware for use in these systems has been developed by Sandia Laboratories, Albuquerque (Veneruso, and Stoller1978) and others for actual status of tool development. LBL (Haney et al., 1980, and Goranson, Schroeder and Solbau, 1980) has developed tools for needs of their in-house field work. d. LBL has developed primitive system (Goranson, 1980).

Table 2-A. Well testing. (continued)

Research Project	Research Task	Annotation on original plan
2. Improved data gathering systems (continued)	g. Develop packing and isolation apparatus for downhole applications such as drill stem testing.	g. LASNL, with industry, has developed an improved system (e.g. Pettitt, 1977)
3. Develop new testing techniques and procedures.	a. Techniques for a simultaneous analysis of mass and heat movement.	a. No work has been done.
	b. New Techniques for crude estimates of well capability (cf. James Method).	b. Prof. Ping Cheng of University of Hawaii supported to evaluate theoretical basis for 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.	a. Significant work on pressure analysis: Tsang and McEdwards (1977), McEdwards (1979), on interference testing, Ramey and others (see Ramey, 1975) on analytical solutions, various specific solutions developed. Little work done on temperature analysis. No work on temporary completion testing because of no interest to test geothermal wells in such a fashion.
	b. Perfect the use of well head values instead of sand face values in analyses.	b. C. W. Miller has investigated relation of wellhead pressure and temperature values as they relate to sand face values (see Miller, 1979 and 1980).

Table 2-A. Well testing. (continued)

Research Project	Research Task	Annotation on original plan
5. Development of methods of analysis of data from passive reservoir response.	a. Analysis of earth tides.	a. Ability to recognize earth tides clearly demonstrated by Narasimhan and Witherspoon (1977), preliminary analysis conducted by Kanehiro (1979) and by Hanson (1979).
	b. Analysis of response to microseisms.	b. No work on microseisms.
	c. Decline curve analysis	c. Decline curves analytical study being conducted by Zais (1979).

Table 2-B. Borehole geophysics

Research Project	Research Task	Annotation on original plan
1. Improve economic and institutional framework.	(Define impediments more clearly; refer to EIB.)	(This entire program became the responsibility of Los Alamos Scientific Laboratory; contact LASNL).
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.	

* Sandia Laboratories Albuquerque

Table 2-B. Borehole geophysics (continued)

Research Project	Research Task	Annotation on original plan
5. Conduct appropriate laboratory experiments related to log interpretation.	b. Evaluate effects of temperature, pressure, salinity on resistivity of saturated porous rock; relate to porosity, permeability, etc. c. Evaluate effect of fractures.	
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. Develope 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 2-C. Geochemical techniques and problems.

Research Project	Research Task	Annotation on original plan
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 movement. b. In analyses of temperature distribution. c. In connection with problems of precipitation within geothermal systems.	1.a,b,c. No summaries of experience have been supported.
2. Investigations of basic geochemistry, including not only equilibrium situations but those having kinetic effects as well.	a. Laboratory studies of reactions rates, partitioning, characteristics, etc., of chemical species of interest with a view to usefulness in understanding mass movement, temperature distribution, and chemical reactions include phase behavior of dissolved gases, physical properties of brines, etc.	a. No basic laboratory studies of reaction rates, partitioning dispersion characteristics, etc., have been supported. USGS covering this area of research.
	b. Field studies of the above.	b. No work has been supported.
	c. Investigate candidates to be used as reactive and nonreactive injected tracers.	c. Candidate materials to be used as tracers are being evaluated by Vetter Research (Vetter, 1980).
3. Application of geochemical techniques and principles.	a. Mass movement analysis.	a. Mass movement in the Cerro Prieto field have been studied to some extent by UC/Riverside through the use of stable isotopes (Elders et al., 1980).

Table 2-C. Geochemical techniques and problems (continued)

Research Project	Research Task	Annotation on original plan
3. Application of geochemical techniques and principles (continued)	b. Temperature distribution studies.	b. Studies by UC/Riverside of mineral distribution in the Cerro Prieto field have been related to current temperature distribution in the field (Elders et al., 1980)
	c. Chemical reactions studies, especially corrosion.	c. No work has been supported. (see LLL* program.)
	d. Mineral deposition studies, especially the formation of scale.	d. Mineral deposition and methods for its possible avoidance or control have been studied for the near-bore area by Michels (1980) and for well plumbing systems by Vetter Research (Vetter, 1979).
	e. Core and cuttings studies.	e. Cores and cuttings have been examined by UC/Riverside as part of their investigations of mineral distribution in the Cerro Prieto field. Although assigned as a research task to UC/Riverside investigation of porosity and permeability through cores and cuttings has not been done (and may have to be reassigned).

* Lawrence Livermore National Laboratory

Table 2-D. Properties of Materials.

Research Project	Research Task	Annotation on original plan
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.	No work has been supported on this topic.
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.	No work has been supported on this topic.
3. Effect of solutes at saturated values on long-term behavior of physical properties of rocks at elevated pressure and temperature.		A program of research on loss of permeability in the near-bore area owing to mud damage was set up with Terra Tek (Butters, personal communication, 1978). Responsibility for coordination of this work has been transferred from DGE-LBL to DGE-Sandia (SLA).
4. New techniques for:	a. Thermal property measurements under chemical and physical conditions relevant to geothermal systems. b. Compressibility and thermal expansion measurement at physical and chemical conditions relevant to geothermal systems.	No work has been supported on this topic.

Table 2-E. Numerical modeling

Research Project	Research Task	Annotation on original plan
1. Evaluation of existent codes.		No comprehensive evaluation of existent codes has been undertaken. However, LBL (and undoubtedly other groups as well) has compared the results of output from its computer codes to various published results. A code comparison RFP has been issued by the Department of Energy.
2. Evaluation of the basic phenomena governing reservoir behavior	a. Physical phenomena	a. No work has been supported.
	b. Chemical phenomena	b. LBL (Iglesias, 1979) has investigated the phenomena of carbon-dioxide and related species in geothermal brines and methods for introducing these phenomena into LBL reservoir performance codes.
	c. Exploitation design	c. No work has been supported.
3. Improvement of numerical models	a. Modeling of two-phase, nonisothermal systems.	a LBL (Pruess et al., 1979) and Princeton University (Pinder et al., 1978) and (Tsang et al., 1978) have improved the methods of solution involved in various numerical codes.
	b. Consideration of effects of fractures near bore region, one-and two-phases.	b. LBL (Narasimhan and Palen, 1979) have applied a numerical simulator to consideration of a near-bore fracture involving one-phase flow. No two-phase near bore fracture problems have been supported.
	c. Effects of fractures away from bore, one-and two-phases.	c. No away-from-the-bore, one or two phase models have been supported.

Table 2-E. Numerical modeling. (continued)

Research Project	Research Task	Annotation on original plan
3. Improvement of numerical models (continued)	d. Simulation of important chemical phenomena	d. LBL has investigated addition of carbonate system chemistry (Iglesias, 1979).
	e. Coupling of reservoir and borehole transport problems	e. Problem of coupling two phase reservoir and borehole transport models is being addressed by LBL (Miller 1980) and Intercomp (Taylor and Aydelotte, 1980).
4. Application to hypothetical but important production/ reinjection strategies		Importance of production/ injection strategies has been addressed by LBL (Tsang, 1978) for Cerro Prieto and (Pruess et al., (1979) for Italian fields. Systems, Science and Software (Pritchett, J. W.,1980) have done such analysis for the Wairakei, New Zealand, field.
5. Inverse problem.		No work has been supported for a systematic evaluation of this problem although all applications of numerical codes address this problem implicitly.
6. Improved numerical techniques.	a. Study of numerical dispersion	a. LBL (Pruess and Schroeder, 1979) and Princeton (Shapiro, 1979) have been concerned with improvements in speed of calculation and also in high precision and accuracy of certain parts of codes (Pruess, 1979).

Table 2-F. Field Case Histories.

Research Project	Research Task	Annotation on original plan
1. Comprehensive documentation of specific sites.	a. Study of East Mesa, California	a. Done by LBL (Howard et al., 1978)
	b. Study of Niland	b. Addressed by LLL (Schroeder, 1976)
	c. Study of Heber	c. No work supported.
	d. Study of Raft River	d. Reported addressed by USGS (Mink, personal communication, 1979).
	e. Study of Roosevelt Hot Springs.	e. No work supported.
	f. Study of Valles Caldera	f. Being addressed by LBL (Tsang et al., 1979).
	g. Study of Cerro Prieto	g. Being addressed by LBL (Lippmann et al., 1979).
	h. Study of Wairakei	h. Addressed by Systems Science and Software (Pritchett, J.W., et al., 1979).
	i. Study of Coso Hot Springs	i. Addressed by LBL (Goranson et al., 1979).
	j. Study of Hawaiian Geothermal Project	j. Status uncertain.
	k. Study of Serrazano-Castelnuovo	k. Various (see Pruess and Schroeder, 1979).
	l. Others, e.g. non-electric field case histories	l. No work supported.
2. Synthesis, generalization and development of conceptual models from field case histories.		

Table 2-G. Modeling the behavior of geothermal systems. Analytical modeling.

Research Project	Research Task	Annotation on original plan
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.	A principal theme to the work being done at Princeton (Saukin et al., 1979).
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.	a. Stanford parallelipiped model Cinco-Ley et al., 1979). b,c. Been investigated to some extent as part of work by Miller (1979).
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.	a,b,c. No work has been explicitly supported.
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.	a,b,c. No work has been explicitly supported.

Table 2-H. Surface Geophysics.

Research Project	Research Task	Annotation on original plan
1. Evaluation of existent techniques - gravity.	a. Define capability for measurement of available instruments	Responsibility for this program was transferred to University of Utah Research Institute, Earth Sciences Laboratory.
	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	
8. Research into improved geophysical methods for exploitation purposes.		

Table 2-I. Physical modeling.

Research Project	Research Task	Annotation on original plan
1. Define more fully the theory of scale modeling for geothermal systems.		1,2,3. Some modeling of physical processes important to geothermal reservoir engineering, namely rock to fluid heat transfer, and two phase one component flow has been done at Stanford (Hunsbedt et al., 1975, Kruger et al., 1978 and Castanier, 1978) No physical analogue modeling of anything analogous to a specific site has been supported.
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 2-J. Economics.

Research Project	Research Task	Annotation on original plan
1. Assess existing economic evaluation methods from other mineral industries.		1,2,3,4. No work on these topics has been supported.
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 alternative energy sources.		

Table 2-K. Exploitation Strategies.

Research Project	Research Task	Annotation on original plan
1. Review and assessment of existent strategies	a. Nongeothermal mineral industries.	1,2,3. No work has been supported.
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 3. SUMMARY OF COMPARISONS (with suggested priorities and levels of effort).

Research Category	Comment	Priority, Level of Effort and Duration
Well Testing		
1.	Continuing effort on analysis of well test results is called for (cf. 4a below).	A-140K/yr-1 yr; $150K/yr-2 thru 5 yrs.
2.a,b,c.	Field testing and redesign following field testing of pressure, temperature, and flow tools is needed	A-$140K/yr-1 yr; $150K/yr-2 thru 5 yrs.
d.	Formal effort on automated well test data gathering system is needed.	C-$50K/yr-3 yr.
e,f.	Continuing effort on mass flow & calorimetry for well head product is called for	C-$150K/yr-3 yr.
g.	Others effort on packers is adequate	E-0-0
3.a.	Level of effort on heat analysis is needed	A-$70K/yr-5 yrs.
b.	James method is good enough	
4.a.	Same as 1	
b.	Need to complete coupling of bore and reservoir simulators	A-$70K/yr-5 yrs.
5.a.	Continuing effort on earth tides and microseisms is appropriate	D-$50K/yr-2 yrs.
b.	ditto	
c.	Continuing data collecting for decline curves is called for	A-$50K/yr-5 yrs.
Geochemical Techniques and Problems		
1.a,b,c.	Apparently available summaries on geochemical techniques and priorities are adequate	E-0 -0
2.a,b.	No specific basic geochemistry research needs are recognized; general cognizance appropriate	D-$25K/yr-5 yrs.
c.	Major field test for tracers required	A-$210K/yr-1 yr; $50K/yr-2 thru 5 yrs.
3.a.	General level of support for stable isotopes to track mass movement is appropriate	B-$100K/yr-5 yrs.
b.	General level of support for studies of isotopes to determine paleo-temperatures is appropriate	B-$100K/yr-5yrs.
c.	No support for corrosion, etc. is appropriate under this program.	E-0-0
d.	Completion of near-bore mineral deposition is called for	B-$100K/yr-3 yrs.

Table 3. SUMMARY OF COMPARISONS (with suggested priorities and levels of effort). (continued)

Research Category	Comment	Priority, Level of Effort and Duration
e.	Important to address possibility of determination of permeability using core and cuttings.	A-$70K/yr-1 yr; $100 K/yr-2 thru 5 yrs
<u>Properties of Materials</u>		
1.a,b,c.	General investigation of electrical conductivity, etc. should get some level of support, guided particularly by needs of bore-hole and surface geophysics; possibly the responsibility of LASL or UURI.	C-$100K/yr-3 yrs.
2.a,b,c.	Measurements of thermal convectivity (relative fluid permeability) are especially needed.	A-$140K/yr-1 yr; $160K/yr-2 thru 5 yrs
3.	No support called for; long-term studies of rock properties are not appropriate to reservoir engineering needs.	E-0-0
4.a,b.	Support for techniques to investigate relative permeability of fracture systems is needed.	A-$80K/yr-5 yrs.
<u>Numerical Modeling</u>		
1.	Evaluation of existent codes is to be done through DOE/SAN.	
2.a.	A review of basic governing equations is appropriate.	B-$50K/yr-3 yrs
b.	A serious effort on introducing the chemical carbonate system into existent codes should be supported.	A-$80K/yr-5 yrs
c.	A preliminary evaluation of exploitation design should be done.	B-$50K/yr-2 yrs.
3.a.	A major effort on code development is still needed (e.g., multicomponent transport).	A-$230K/yr-1 yr; $280K/yr-2 thru 5 yrs.
b,c.	Continuing effort on modeling fractures is needed.	A-$80K/yr-5 yrs.
d.	(A part of 2B, above)	
e.	Coupling activity should be satisfactorily concluded; same as well testing 4.b.	
4.	Application to hypothetical examples are important and deserve continuing support.	A-$80/yr-5 yrs.
5.	The inverse problem should be evaluated.	C-$50K/yr-3 yrs.
6.	(A part of 3a, above)	

Table 3. SUMMARY OF COMPARISONS (with suggested priorities and levels of effort). (continued)

Research Category	Comment	Priority, Level of Effort and Duration
Field Case Histories		
1.a.	Current study of East Mesa is adequate.	E-0-0
b.	Update of Niland is called for.	B-$50K/yr-2 yrs.
c.	Data base for Heber is lacking; also being done by industry.	E-0-0
d.	Update of Raft River is called for.	A-$50K/yr-1 yr.
e.	Update of Roosevelt is called for; data base is limited.	C-$50K/yr-1 yr.
f.	Work on Valles Caldera is planned by DOE R/A.	A-$400K/yr-4 yrs.
g.	Unusual opportunity for complete data base at Cerro Prieto should be utilized.	A-$700K/yr-1yr; $750K/yr-2 yr; $800K/yr-3 yr.
h.	Follow-up to S^3 work on Wairakei is appropriate.	B-$100K/yr-3 yrs.
i.	Modest add-on at Coso is reasonable.	B-$25K/yr-2 yrs.
j.	Some effort at Hawaii would be beneficial.	A-$20K/yr-3 yrs.
k.	Serrazano-Castelnuovo (Funded as a part of Numerical Modelling 3.a.).	
l.	Nonelectric case histories, in general, require some effort.	A-$90K/yr-1 yr; $100K/yr-2 thru 5 yrs.
2.	Synthesis of all field experience is very important and should no longer be neglected.	A-$90K/yr-1 yr; $100K/yr-2 thru 5 yrs.
Analytical Modeling		
1.	Princeton effort on basic formulations is adequate.	A-$40K/yr-3 yrs.
2.a,b,c.	Analytical well test analysis is the core activity of this subject; same as Well Testing 1.	
3.a,b,c.	Problems in heat transfer deserve some effort.	C-$50K/yr-5 yrs.
4.a,b,c.	Problems of conduction and convection are important, if somewhat academic, and deserve some support.	D-$25K/yr-3 yrs.

Table 3. SUMMARY OF COMPARISONS (with suggested priorities and levels of effort). (continued)

Research Category	Comment	Priority, Level of Effort and Duration
Physical Modeling		
1,2,3.	Physical analogue modeling serves no special advantage over numerical simulation and requires no support.	E-0-0
	Modeling of boiling and relative permeability are critically important; included as part of Properties of Materials 2.a,b,c.	
Exploitation Strategies		
1,2,3.	Some support is warranted for this research category.*	A-$60K/yr-1 yr; $100K/yr-2 yrs.
Economics		
1.	Some support on economics of other mineral industries and their applicability to geothermal would appear warranted.	B-$50K/yr-2 yrs.
2.a,b.	Case studies of the economics of successes are highly desired by investors.	A-$60K/yr-1 yr;** $100K/yr-2 thru 5 yrs.
3.a,b.	A key hangup to investors is the measure risk; an effort here is required.	A-$60K/yr-1 yr; $100K/yr-2 thru 5 yrs.
4.	Comparative economics are desirable and should be considered under 1 above.	

* A number of ideas on presently incompletely investigated strategies were called to our attention recently by Dr. M. W. Molloy and Prof. H. J. Ramey, Jr. Although we cannot expand fully on these strategies we do wish to make record of them because of their importance. They include the following questions: Should boiling be induced in the formation in hot water reservoirs; should hot water be maintained as one phase by pumping to the wellhead; how is injection of spent fluid best handled; when should stimulation be called upon.

** To be handled via Baca and other demonstration projects.

Table 4. List of Top Priority Needs and FY '81 and Following Budgets.

Research Category	Needs	Minimum Budget '81	'82	'83
Well Testing	*Improved data gathering	140	150	150
	*New testing techniques and tools	140	150	150
	*Wellhead versus sand face	70	70	70
	+Decline curves	50	50	50
	*Heat analysis	70	70	70
Geochemical techniques and problems	*Major tracer field test	210	50	50
	*Porosity and permeability from cuttings and cores	70	100	100
Properties of materials	+Thermal convectivity and relative permeability - porous material	140	160	160
	*Ditto - fractured materials	80	80	80
Numerical modeling	*Additional modeling of carbonate systems	80	80	80
	*+Code development	230	280	280
	*Fracture modeling	80	80	80
	+Applications, injection studies	80	80	80
Field case histories	+Raft River	50	0	0
	+Valles Caldera ***			
	+Cerro Prieto	700	750	800
	+Hawaii	20	20	20
	+Nonelectrical	90	100	100
	+Synthesis	90	100	100
Analytical modeling	Basic formulations, see also Well Testing	40	40	40
Physical modeling	Work noted under Properties of Materials	Addressed elsewhere in this table.		
Exploitation strategies**	Reservoir management	60	100	100
Economics	+Risk analysis and statistics	60	100	100
		2500	2610	2660

* Technical impediment
\+ Credibility related
** Economics need
***$400K/yr-4 yrs DOE/SAN (not included in total below)

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APPENDIX

GREMP Steering Committee Remarks Summary

Major Problem Areas in DOE-Funded Reservoir Engineering Research

(December 11, 1979 Meeting at Palo Alto)

The main concerns of the group may be summarized as follows:

1. The funding level for direct GREMP research and GREMP-inspired research (i.e., logging instrumentation and logging interpretation) has been very low relative to its importance to geothermal commercialization. Every study we are aware of dealing with technical impediments to commercialization, including studies by the DOE and EPRI, has concluded that assessment of reservoir producibility and reserves is critical. In fact, improvement in techniques for such assessments is of fundamental importance; much more so at this stage of the industry's development than improvements in exploration techniques, drilling cost reductions, etc. We strongly recommend increases in GREMP and GREMP-related funding in proportion to their true importance.

2. In addition to the low level of funding, the lack of continuity in DOE leadership, leadership by persons with experience in inappropriate disciplines, and lack of coordinated leadership (for GREMP, logging instrumentation, logging interpretation, rock properties, and related exploration research) by DOE has in part been responsible for less than optimal results thus far. We recommend a single program manager be in charge of all the separate GREMP and GREMP-related research and/or an integration of such research programs into a single program under a single DOE manager.

3. The planned emphasis upon low-temperature, nonelectric research by the DOE and downgrading of high-temperature electrical generation research is premature. Many of the problems requiring research outlined by GREMP more than three years ago are still existent. Most areas of concern have been attacked, but few research efforts have reached a level of results sufficient to clearly support the conclusion that commercialization of high-temperature resources for electric power generation is at hand and needs little further DOE support. Furthermore, even if emphasis on nonelectric research were appropriate at this time, GREMP research is equally fundamental to commercialization of such low-temperature resources and deserves substantial DOE support.

4. The planned future emphasis on RFP's in preference to unsolicited proposals will effectively eliminate participation by university and national laboratory groups. Some mechanism needs to be provided for continued participation in reservoir engineering research by such organizations.

Prepared by D. A. Campbell

GEOTHERMAL RESERVOIR ENGINEERING MANAGEMENT PROGRAM AT LBL

Review Meeting

Palo Alto, California, December 11, 1979

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