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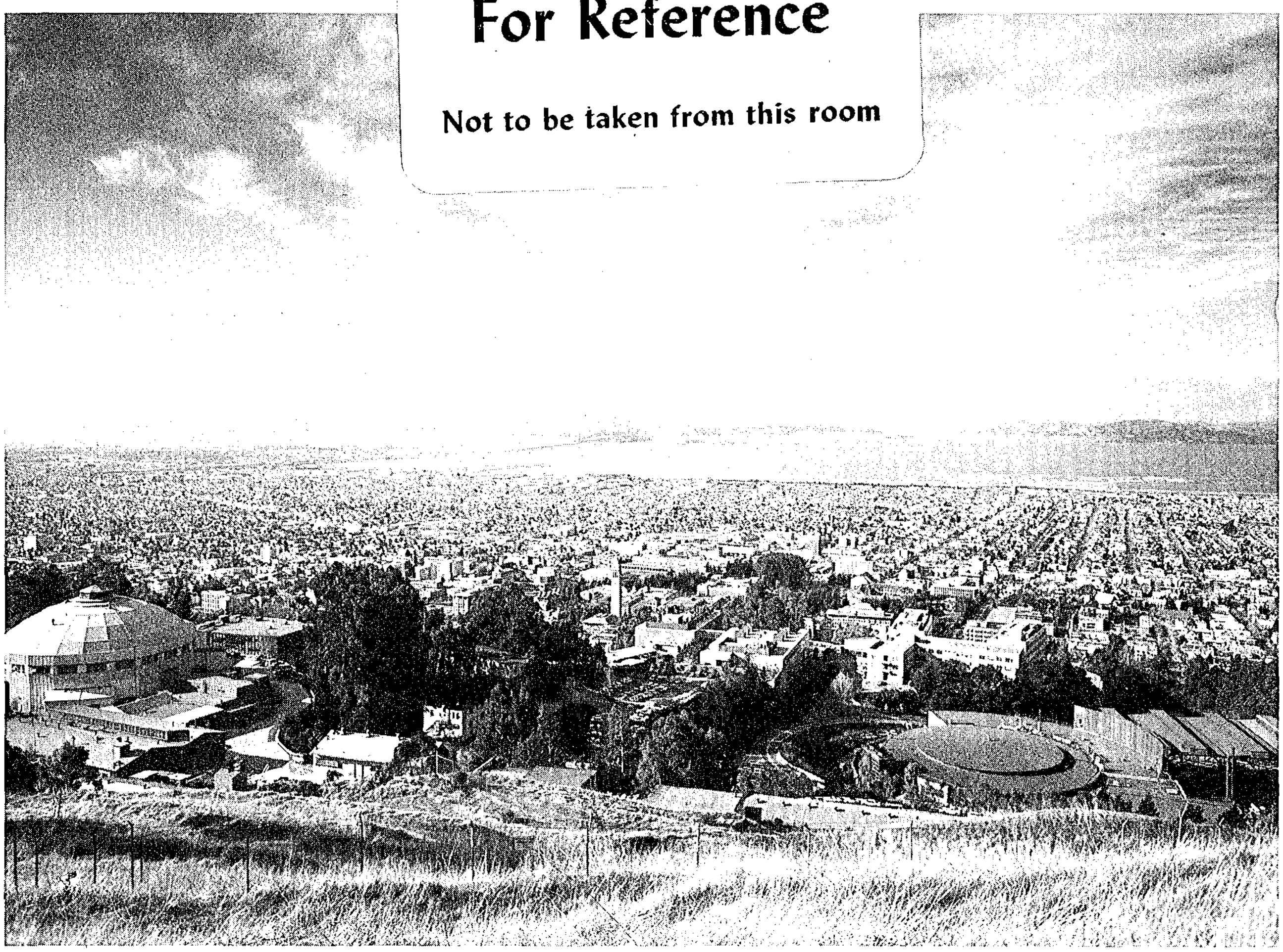

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

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1. INTRODUCTION

The newest division at the Lawrence Berkeley Laboratory (LBL), the Earth Sciences Division, was formed in 1977 from the Energy and Environment Division's geosciences group. In the five years since the latter group was formed, its technical scope has expanded from projects on geothermal exploration to those encompassing geothermal reservoir engineering and geothermal energy conversion, nuclear-waste isolation, enhanced oil recovery, thermal energy storage, uranium resource assessment,, and the fundamental geosciences. The strength of the Division lies in its ability to combine expertise in the geosciences with the engineering, technical, chemical-analytical, and computational support available in other LBL divisions.

In terms of funding, the geothermal and nuclear-waste isolation programs are the largest; they are supported primarily by the U.S. Department of Energy's (DOE) Division of Geothermal Energy and Office of Waste Isolation. Fundamental geosciences encompass projects of a more basic nature, supported primarily by DOE's Division of Basic Energy Sciences, and to some extent by development funds of the director of LBL. Projects in applied geoscience are funded by other divisions of DOE or by other government agencies, either directly or by subcontract.

International projects of the Division, described in some detail in this report, include cooperative projects with government agencies in Sweden, Italy, and Mexico. The Swedish project, a part of the research program in nuclear-waste storage, is a study of thermal and hydrological effects of radioactive waste storage in deep crystalline rock masses. It is being conducted at a granite site, about 200 km north of Stockholm. The cooperative project with Mexico's Comisión Federal de Electricidad investigates the geologic setting and reservoir characteristics of the Cerro Prieto geothermal field in Baja California. The project will monitor long-term changes in the field as it is produced. The joint U.S.-Italian program studies the effects on the reservoir of production from the Larderello geothermal field, the world's oldest producer of geothermal electric power.

The Division effort includes the participation of mechanical engineers, electrical engineers, reservoir engineers, physicists, geologists, geophysicists, and geochemists. Close ties are maintained with the faculty members and staff of the University of California. Several faculty members, postdoctoral scientists, and a significant number of graduate students have research positions in the Division.

The research projects reported here serve to demonstrate the versatility of the Division in attaining its goal, which is to furnish a high level of expertise in addressing a broad range of geoscience problems, and to identify and respond to future challenges in geoscience.

EARTH SCIENCES DIVISION

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2. FUNDAMENTAL GEOSCIENCES

Fundamental Geoscience studies at the Lawrence Berkeley Laboratory consist of three major programs: geosciences relating to geothermal energy, development of techniques for precise measurement of physical and chemical properties of geological materials in order to understand geological phenomena, and a developmental program that includes new and promising geoscience studies with a variety of applications in energy resource development.

The geoscience program relating to geothermal energy consists of four projects. In the project on reservoir dynamics, sophisticated codes have been written to simulate the dynamics of heat flow in geothermal reservoir systems. These codes have also been applied to the investigations of natural aquifers as a storage system for thermal energy. In the second project, core samples are studied to determine the high temperature and high pressure behavior of aquifers in the presence of saturating fluids. The third project covers the systematic evaluation of the thermodynamic properties of electrolytes in order to interpret the behavior of geothermal fluids. The fourth project involves hydrothermal solubility measurements of various minerals to elucidate the chemistry and mass transfer in geothermal systems.

The second major program includes four projects which involve precise measurements and analysis of physical and chemical properties of geologic materials. These include measurements of the thermodynamic properties (viscosity, density and heat capacity) of silicate materials to help understand magma genesis and evolution, high-precision neutron activation analysis of rare and trace elements in magmatic materials, and the precise measurement of seismic wave velocities near geological faults, in order to determine the build-up of stress in the earth's crust. Support is also provided for the National Geothermal Information Resource (GRID) project, in which the current literature is searched for experimental data of relevance to the geothermal energy industry. Reports are published periodically summarizing and critically reviewing the data.

Third, the development program in fundamental geosciences includes six innovative projects providing techniques applicable to energy resource development. These projects include research in the in situ leaching of uranium ore, properties of magmas, removal of pyrite from coal, properties of soils and soft rocks, stress flow behavior of fractured rock systems, and high-precision mass spectrometry.

ON SOME FUNDAMENTAL ASPECTS OF RESERVOIR DYNAMICS

T. N. Narasimhan, M. J. Lippmann, and P. A. Witherspoon

This report summarizes the research activities of the authors during fiscal 1977 on some fundamental aspects of reservoir dynamics. The research work touched upon the following: constitutive laws; chemical transport; land subsidence; flow in fractured media; and numerical modeling of the non-linear diffusion equation.

CONSTITUTIVE LAWS

It is now well recognized that the release of stored fluids from most hydrogeological systems is dominated by a reduction in the pore volume of the reservoir. While fluid flow is governed by pore-pressure changes, the skeletal deformation is caused by the stress changes on the matrix. For modeling fluid flow in deforming media, a fundamental necessity is therefore a constitutive relation between pore-pressure change and the effective stress (skeletal stress) change. For saturated systems it is customary to use

$$\sigma' = \sigma - \psi \rho_\omega g \qquad (1)$$

where σ' is the effective stress, σ is the total stress, ψ is the pore-pressure head, ρ_ω is the density of water, and g is the gravitational constant.

Although (1) has generally been satisfactory for saturated systems, its extension to unsaturated or two-phase systems has been questionable. It is customary in the soil physics literature to neglect the possibility of matrix deformation in the unsaturated zone and effectively set $\sigma' = \sigma$. On the other hand, extensive work in the deformation of unsaturated soils has given rise to the modified constitutive law[1]:

$$\sigma' = \sigma - \chi \rho_\omega g \psi \qquad (2)$$

where $0 \leq \chi \leq 1$ and $\chi = \chi(\psi)$ in the unsaturated zone. Or, in a generalized fashion,

$$\sigma'_{ij} = \sigma_{ij} - \chi \rho_\omega g \psi \delta_{ij} \qquad (3)$$

where δ_{ij} is the Kronecker delta.

A constitutive law of the form (2) or (3) is essential, not only for properly unifying flows in the saturated and the unsaturated domains, but also for understanding such field phenomena as ground fissuring in heavily dewatered aquifers in arid zones and the subsidence associated with organic soils.

The aforesaid concepts were discussed in a presentation entitled, "The Significance of the

Storage Parameter in Saturated-Unsaturated Flow" presented before the American Geophysical Union.[2]

CHEMICAL TRANSPORT

The transport of reactive or non-reactive species in flowing groundwater is of fundamental interest in many branches of earth sciences (e.g., radioactive waste disposal and geothermal reinjection). Mathematically the mechanism of chemical transport is customarily simulated by the convective-diffusion equation of the form

$$\nabla \cdot D\nabla C + v \cdot \nabla C = \frac{\partial C}{\partial t} \quad (4)$$

where D is a diffusion coefficient, v is the pore-velocity of the fluid and C is concentration. While the numerical simulation of (4) is generally satisfactory when D is large (i.e., diffusion dominates convection), the solutions are affected significantly by numerical dispersion when D is relatively small (convection-dominated systems). Recent field investigations seem to suggest that many field situations may be characterized by low diffusion. Therefore, ability to successfully handle convective-dominated diffusion problems is of considerable practical interest.

A study of the formulation of the convective diffusion equation suggested that reformulating the problem directly in an integral form and re-examining the solution procedure will greatly help minimize the problem of numerical dispersion. Accordingly, work was commenced during the summer of 1977 to solve the one-dimensional convective diffusion equation by integral methods. By the end of summer, the preliminary calculational model was developed and favorable comparisons achieved with analytical solutions of low diffusion problems.

LAND SUBSIDENCE

Numerical models for simulating reservoir compaction in isothermal[3] as well as non-isothermal[4] systems have already been developed at LBL. These models, however, do not include the propagation of reservoir deformation to the land surface through the overburden, especially when the reservoir is buried at a great depth. If we recognize that reservoir deformation is primarily caused by the internal loading process of pore-pressure withdrawal and that the overburden deforms are the boundary displacements imposed at the reservoir-overburden boundary, it becomes apparent that an efficient and economic way of modeling land subsidence is to employ a dual model using the existing models[3,4] (which have been found so very well suited for reservoir deformation) for simulating the reservoir and use the more general (and expensive) non-linear finite element models for simulating the overburden deformation. Accordingly, work was initiated during the second half of the year on a very general pseudo-elastic finite element model for overburden deformation. By the end of the year, this model, developed by W.N. Houston and A.G. Kasim of the Department of Civil Engineering, University of California at Berkeley, was being used for parametric studies on a two-layered system. The results are slated to be presented in the Engineering Research Conferences of the American Society of Civil Engineers, Pensacola, Florida, January, 1978.

FLOW IN FRACTURED POROUS MEDIA

It is known from field experience that many geothermal wells and deep waste disposal wells may be intersected by natural or artificial fractures. Although, in general, the reservoir could be idealized as a porous medium, the fractures may so dominate the flow near the well that due consideration will have to be given in modeling the pressure transient behavior of such wells. In the literature, analytic techniques (e.g. the Green's functions[5]) as well as semi-analytic techniques[6] have been used to study flow to fractured wells. However, these techniques are limited by the constraints imposed on analytic solutions. In order to be able to handle arbitrarily complex problems, the numerical model developed earlier by Narasimhan and Witherspoon[7,8] was applied to the study of near-well flow phenomena in wells intercepted by finite conductibility vertical fractures. The validity of the model was successfully verified by comparison with known analytic and semi-analytic solutions. The ability of the model to handle well-bore storage and deformable fractures was also verified.

NUMERICAL MODELING OF THE NON-LINEAR DIFFUSION EQUATION

The mathematical simulation of groundwater systems leads to the consideration of a non-linear, parabolic differential equation of the form

$$\nabla \cdot K(\phi)\nabla\phi = S(\phi)\frac{\partial \phi}{\partial t} \quad (5)$$

where K is permeability, ϕ is potential and S is the storage coefficient. It is well known that equation (5) could be numerically solved using the method of finite differences, integrated finite differences, or finite elements. It was shown[9] by Narasimhan et al. that one could maximize the advantages of the integrated finite differences and the finite elements by combining them into a single algorithm in which the conductance matrix is formed using the finite element approach, and the solution process is carried out using the mixed explicit-implicit strategy used in the integrated finite difference scheme. During fiscal 1977, the applicability of the new approach to subsurface hydrology problems was demonstrated.[10] In addition work was initiated in the summer to prepare a users' guide (with examples) for the new algorithms (called FLUMP); this work was continuing at the end of the year.

PLANNED ACTIVITIES

During 1978, the users' guide for FLUMP is expected to be completed. Research work on all the other aspects referred to above will be continued.

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THERMAL ENERGY STORAGE IN AQUIFERS

C. F. Tsang and M. J. Lippmann

INTRODUCTION

The development of practical and low-cost methods for storing large amounts of thermal energy is of fundamental importance for the utilization of solar energy as well as the implementation of total energy systems. The basic function of a storage system is to act as a buffer between time-varying energy inputs and thermal and/or power demands. The purpose of the present project is to study the feasibility of storing hot water in natural aquifers underground. The purpose is to understand the hydrodynamic and thermal behavior of an aquifer, to estimate the efficiency of thermal storage and retrieval, and to suggest optimal arrangements for implementation.

Aquifers are geologic formations that contain and conduct water. They are found at depths ranging from a few meters to several kilometers. Confined aquifers are those bounded above and below by impermeable layers and saturated with water under pressure. For many years such aquifers have been used for liquid waste disposal and for storing fresh water, oil products, and gas. However, their use for hot water storage is a relatively new concept suggested by Robbimov et al.,[1] Kazmann,[2] and Meyer and Todd[3] in the early 1970's.

The physical basis of the concept of storing hot or cold water in aquifers lies in : (1) the low thermal conductivities of caprock and bedrock materials, (2) the large volumes of many aquifers (of the order of $10^7 m^3$), and (3) the capability of storing water under high pressures. To estimate the feasibility and efficiency of such a storage system, the behavior during injection and withdrawal cycles must be understood, such as: (1) thermal behavior of and heat loss from the system during successive cycles of operation; (2) pressure distribution in the aquifer during the process; and (3) rock-water chemical reactions and the resulting change in aquifer permeability.

It is only recently that sophisticated computer models have been developed to study these questions using the proper physical conditions and parameters, and to make realistic predictions of the energy recovery efficiency of aquifer storage systems. Furthermore, physical models and field experiments[4,5] have been initiated to test this concept. These will not only provide data to verify numerical models, but also give an indication of the feasibility and possible problems that may be encountered during the implementation of the aquifer storage concept.

THIS YEAR'S ACTIVITIES

In this project, which was started December 1976, we made use of a numerical model developed at the LBL to investigate hot and chilled water storage. The numerical model employed is called "CCC" which stands for "Conduction, Convection, and Compaction."[6,7] It is based on the so-called integrated-finite-difference method.[8] The model computes heat and mass flow in three-dimensional water-saturated porous systems. Concurrent with the mass and energy flow, the vertical deformation of the aquifer system is simulated using the one-dimensional consolidation theory of Terzaghi.[9]

Thus the following physical effects can be included simultaneously in the same calculations.

- Flow of hot and cold water with large viscosity and density differences
- Effects of temperature on rock and fluid properties (e.g., heat capacity, viscosity, and density)
- Heat convection and conduction in the aquifer, caprock and bedrock
- Effects of gravity on fluid flow
- Effects of regional groundwater flow
- Combined effects of many injection and withdrawal cycles
- Spatial variations in aquifer properties.
- Possible compaction and the associated land subsidence due to pressure changed during the injection-withdrawal history

Five different cases have been studied:

1. Hot water daily storage: hot water is injected for 12 hr during daytime and produced for 12 hr during nighttime.
2. Hot water seasonal storage, semiannual cycle: hot water is stored in spring for 90 days, pumped to use for air-conditioning in summer for 90 days, then hot water is again stored in autumn for 90 days and finally pumped out to use for heating in winter for 90 days.
3. Hot water seasonal storage, annual cycle: hot water is stored in summer for 90 days and used for 90 days in winter for heating. There is no injection or production during spring or fall.
4. Chilled water seasonal storage: chilled water (at 4°C) is stored in winter for 90 days and produced for 90 days in summer to be used for air-conditioning. There is no injection or production during spring or fall.
5. A two-well (doublet) system: during storage period, water is produced from well, heated and then injected into the other one; during the utilization period, hot water is retrieved from the latter and the cooled, used water is injected back into the former.

The rates of injection and production are kept the same, equal to 10^6 kg/day.

The initial temperature of the aquifer in all cases is assumed to be 20°C. For Cases 1 through 3 we have performed calculations with injection temperature T_i assumed to be 120°C, 220°C, and 320°C. It appears that the temperature of the produced water for different injection temperatures approximately scales according to the factor $(T_i - T_o)$. For Case (4), only one injection temperature, 4°C, has been used. Some typical results are shown below.[10]

For Case 2, seasonal storage, semiannual cycle, we have performed calculations not only for a well fully penetrating the aquifer (thickness 100 m) but also for a well partially penetrating the aquifer for 50 m. Figure 1 displays the temperature contours within the aquifer for the partial penetration case (1) at the end of the injection period of the first cycle and (2) at the end of the production period of the same cycle. The thermal front is not sharp due to heat conduction within the aquifer and within the confining beds.

Figure 2 represents the production temperature at the well during the production period for

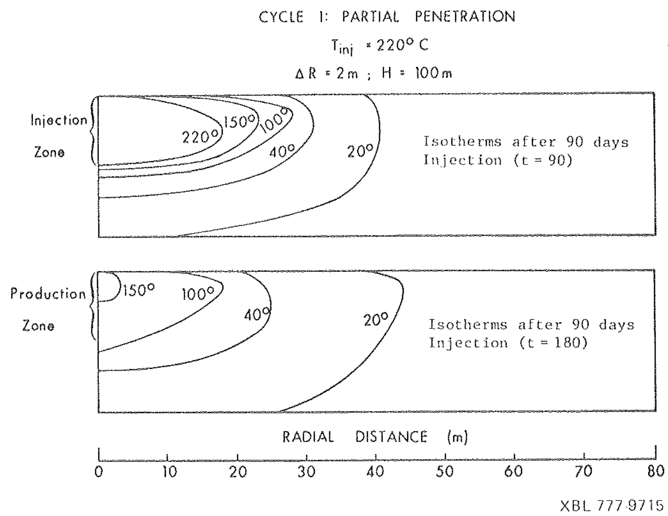


Figure 1. Temperature contours in the aquifer after 90 days of injection and after 90 days of production in Cycle 1, for the case of semiannual cycle, seasonal storage. The well penetrates the upper 50 m of the aquifer. Numbers labeling the contours are in degrees Celsius.

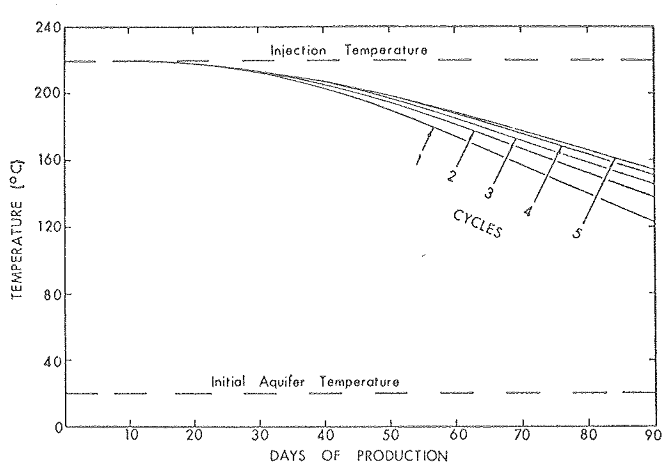


Figure 2. Temperature at the well versus production time for each cycle. The case shown is for seasonal storage with semiannual cycle; well fully penetrates the aquifer.

Table 1. Summary of results: semiannual cycles with full penetration.

	CYCLE				
	1	2	3	4	5
Energy injected, joules	5.71×10^{13}	5.71×10^{13}	5.7×10^{13}	5.71×10^{13}	5.71×10^{13}
Energy recovered, joules	4.96×10^{13}	5.092×10^{13}	5.144×10^{13}	5.18×10^{13}	5.2×10^{13}
Energy loss from aquifer, joules	5.34×10^{11}	6.81×10^{11}	7.7×10^{11}	8.41×10^{11}	9.1×10^{11}
Energy diffused to heat up aquifer, joules	7.10×10^{12}	5.5×10^{12}	4.9×10^{12}	4.46×10^{12}	4.2×10^{12}
Percentage of energy recovered	86.8	89.2	90.0	90.7	91.1
Production temperature at end of cycle, °C	124	139	147	151	155

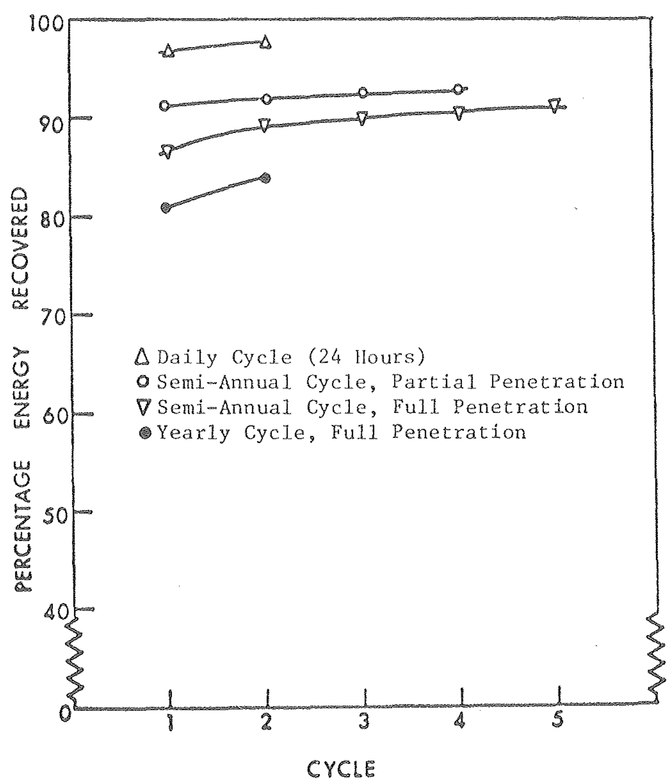
Full penetration: 1 Cycle = 180 days, T_i = 220°C, T_o = 20°C, Q = 1×10^6 kg/day, H = 100 m, ΔR = 2m, no. of layers = 4.

successive cycles for the case of semiannual cycle with full penetration. The recovery temperature is increased for each successive cycle as the aquifer is heated up, making it a more efficient hot water storage system. The process will reach quasi-equilibrium when later cycles do not change the temperature appreciably.

The results for semiannual cycles with full penetration are summarized in Table 1. It can be seen that the energy recovered (which may be calculated from the integral of temperature over time in Fig. 2) improves with each successive cycle. The heat lost is also shown and is two orders of magnitude smaller than the energy recovered. The difference between energy injected and recovered is the energy diffused to heat up the aquifer, making it a better storage system for the following cycle. The last line gives the minimum recovery temperature during production. This corresponds to the lowest temperature found at the end of each production period, as shown in Figure 2.

For Cases 1 through 3 the percentage of energy recovered (i.e., recovered energy divided by total injected energy) during each cycle is plotted against cycle number in Figure 3; the values shown in Figure 3 are surprisingly high (>80%).

For Case 4, where chilled water is stored, the temperature of production during the summer is shown in Figure 4, and the highest temperature during production (at the end of the production period) versus cycle number is shown in Figure 5.



XBL 777-9717

Figure 3. Percentage of energy recovered over energy injected versus cycle number.

Thus after three cycles, the temperature during production is expected to stay below 10°C during the whole production period.

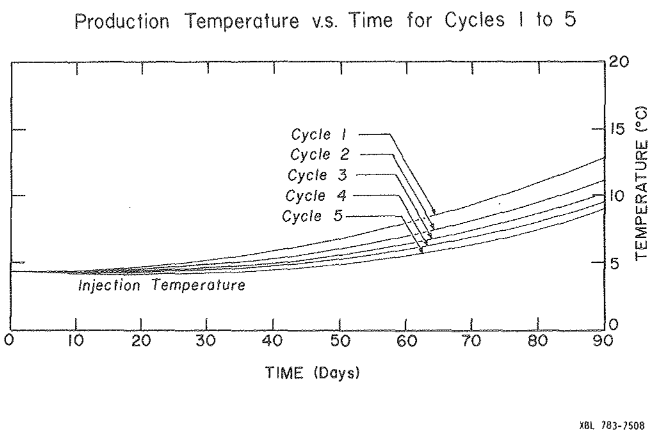


Figure 4. Chilled water storage: temperature at the well versus production time for each of the Cycles 1 to 5.

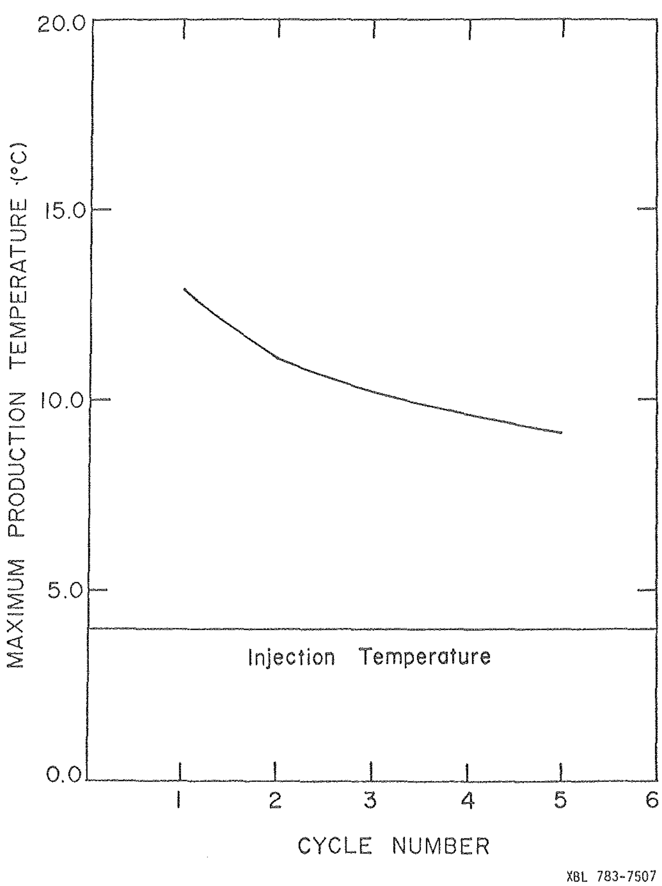


Figure 5. Chilled water storage: temperature at the end of each production period (maximum production temperature) versus cycle number.

FUTURE ACTIVITIES

During the next fiscal year, the following tasks will be addressed.

1. Further calculations will be done for a "typical" aquifer system, exploring the effects of variations in parameters, such as thickness, permeability, flow rates, and boundary conditions.

2. Further calculations will be made for multiple-well systems with the goal of identifying optimal arrangements for heat storage and retrieval.

3. Collection and evaluation of field data collected from thermal storage field experiments (e.g., those of Auburn University). Suggestions may be made to the experimenters for new or additional measurements. We will draw from the LBL expertise in geophysical studies and well-test analysis.

4. Modeling of these field cases will be made using our numerical model. This will (1) validate our model, (2) possibly suggest new crucial experiments that should be done, and (3) possibly indicate optimal implementation procedures for the hot water storage concept.

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PROPERTIES AND BEHAVIOR OF ROCK-FLUID SYSTEMS AT HIGH TEMPERATURES AND PRESSURES

W. H. Somerton

INTRODUCTION

The objectives of this project are to determine the physical properties and behavior of rock-fluid systems under environmental conditions encountered in geothermal reservoirs or in other subsurface thermal operations. Because these properties are difficult to measure and require a great deal of time for each measurement, a second objective is to develop models and correlations which will permit estimation of properties and behavior from other more easily determined characteristics of the system. These relations should then be useful in modeling subsurface reservoir behavior.

This project provides rock properties data for other Earth Science Division projects. In particular, thermal data have been provided for several geothermal and similar projects. Data are also available on flow and storage capacity of rocks at high temperatures and other properties of rocks related to borehole stability, subsidence prediction, and interpretation of well-log and geophysical data.

In earlier work, a good deal of equipment and techniques for measuring rock properties has been developed. Several models and correlations of rock behavior have been developed; they are being improved as new data are obtained.

THIS YEAR'S ACTIVITIES

Principal emphasis in this year's work has been on the thermal properties and behavior of a large range of rock types. These include volcanics, basalts, limestones, and a wide range of sandstones, siltstones, and shales. Some work has also been done on unconsolidated sands (including tar sands) and drill cuttings. These data are being cataloged and tested against previously developed models and correlations. Work is continuing on an improved 3D model of heat flow through multi-fluid saturated porous media to aid in the correlation work. The computer program for calculating specific heats from oxide analysis has been revised and updated so that thermal diffusivity data can be provided for the above rock-fluids systems.

Work was completed on the study of P and S wave velocities at elevated temperatures.[1] The apparatus for measuring these properties simultaneously on fluid-saturated rocks was tested and found to perform satisfactorily. From data generated for several sandstones, it was possible to calculate dynamic elastic properties useful in borehole stability and fracturing studies. The ratios of S-to-P wave velocities were found to correlate well with the degree of liquid saturation, leading to the possibility of detecting vapor-liquid boundaries from borehole velocity measurements. Because the ratio of the velocities squared is directly proportional to Poisson's ratio, this modulus also shows a direct correlation with degree of liquid saturation.

Measurements of fluid flow capacities of rocks at high temperatures are continuing to show a larger than expected effect. Liquid permeabilities are found to decrease by factors of 4 to 5 when the temperature is increased to 200°C. No permanent structural damage appears to occur; air permeability tests before and after heating show no significant change in permeability. The system is being redesigned so that pressure drops will be measured directly across the core rather than with external measurements which require system pressure loss corrections. Further tests will be made to evaluate the brine sensitivity of cores at elevated temperatures.

A new apparatus was designed and constructed for the measurement of both bulk and pore compressibilities at elevated temperatures. From this apparatus, the effects of temperature and pore pressure on rock storage capacity can be determined. This same apparatus may also be used to determine pore and bulk thermal expansions of liquid saturated rocks.

Construction of the new high temperature rock properties apparatus was not started because of the uncertainties of private sector funding. Grant requests were made to three oil companies who had expressed positive interest in supporting this work. These requests were made late in the year and at this writing, no response has yet been received.

ACTIVITIES PLANNED FOR NEXT YEAR

All work described above, with the possible exception of velocity measurements, will be continued in the coming year. Principal emphasis again will be on thermal measurements and correlations with the goal of preparing and publishing a manual on thermal properties and behavior of rock-fluid systems. Continued efforts will be made to improve fluid flow capacity measurements and to gain an understanding of the seemingly excessive temperature effects on permeability. The new apparatus for study of storage capacities will be tested, and by midyear data will be taken and analyzed for the effects of temperature and pore pressure on this property. It is to be hoped that funding for the new rock-properties apparatus will be complete so that construction may be started early in the year.

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THERMODYNAMICS OF HIGH TEMPERATURE BRINES

K. S. Pitzer, L. F. Silvester, P. Z. Rogers, and J. R. Peterson

INTRODUCTION

An understanding of brines is essential for the technical utilization of many geothermal resources. Consequently, a study of the solution thermodynamics of brine systems, both simple and complex, weak and strong, covering a wide temperature and pressure range, and combining both modeling and experimental work began in 1975.

The initial work involved analysis of existing thermodynamic data on simple electrolyte systems using equations developed by Pitzer and coworkers.[1-4] The goal of the modeling was to provide a compact set of equations capable of reproducing at various temperatures and pressures the existing data within experimental error up to practical concentrations (~6M) in terms of parameters having physical significance. The modeling equations for NaCl(aq) solutions were integrated into GEOTHERM, an LBL computer program for modeling geothermal power plants.[5]

The program to measure heat capacities arose because of inadequate literature data on electrolyte systems. The experimental program has two goals: (1) to supply data on simple and complex electrolyte systems previously unreported, plus extending existing data to higher temperatures and pressures both along and away from the liquid-vapor saturation curve; and (2) to provide a data base for checking and refining various models.

Although the modeling and experimental work relate directly to electrolyte systems common to geothermal brines, the results are applicable to such areas as biological fluids, battery electrolytes in aqueous and nonaqueous solvents, plating baths, waste effluents, materials corrosion from electrolyte systems, and marine chemistry.

PROGRAM IN 1977

During the period of this report the modeling calculations emphasized sulfuric acid and the rare earth salts which are the subjects of separate sections below. In addition the work on sodium chloride, reported last year,[6] was extended to deal with the solubility of solid NaCl and was prepared for journal publication.[7]

A national chemical engineering conference requested K.S. Pitzer to prepare a paper on the origin of the acentric factor and its use in modeling normal fluid properties. This paper[8] was presented as the opening lecture at the Conference on Estimation and Correlation of Phase Equilibria and Fluid Properties in the Chemical Industry, January 1977. In addition to the history and original rationale of the acentric factor, a brief review was given of recent developments in this area.

The development and testing of a high temperature flow calorimeter continued during this period. Various problems in control and measurement were overcome but at a rate limited by the personnel time available. Further improvements are required before satisfactory measurements will be possible but we believe these are feasible.

Sulfuric Acid

In contrast to a strong acid, such as hydrochloric, only the first dissociation of sulfuric acid is complete. For our modeling calculations, the equations for the partial dissociation of the bisulfate ion HSO_4^- were added to the regular set of equations for the ions present. The primary data set included results for three electrochemical cells over the temperature range 0°-60°C together with water vapor pressure and heat of dilution data for 25°C. Our analysis covered the composition range from 0 to 6 molal. In each of the cells, the H^+ activity was measured with a hydrogen electrode; that of $SO_4^=$ was determined by lead, lead sulfate; mercury, mercurous sulfate; or lead dioxide, lead sulfate electrodes, respectively.

There is no difficulty in obtaining concordant results for the range above 0.1 M but conflicts between data arise for the very dilute solutions. In this range, results were considered also for a fourth electromechanical cell which measured mixed H_2SO_4-HCl solutions and used the silver, silver chloride electrode. While the conflicts remain and alternative parameters were reported, the preponderant evidence favors the parameter set including a dissociation constant of 0.0105 for HSO_4^- at 25°C. Either set of parameters reproduce satisfactorily all data above 0.1 M; hence, there is no real uncertainty for many practical applications.

The numerous equations and parameters are now published[9] along with the results of several secondary calculations made possible with this treatment. Rabindra N. Roy, a visiting scientist in the summer of 1976, participated in the work on sulfuric acid.

Rare Earth Chlorides, Nitrates, and Perchlorates

In a very extensive series of papers Spedding and associates have presented various thermodynamic data for the nitrates, chlorides, and perchlorates of most of the rare earths. While excellent comparative treatments of the results for any one series are given in these papers, it seemed to us to be of some interest to fit a general array of these data to a single type of equation. We have considered the osmotic coefficient, the heat of dilution, and the volumetric data for all of the chlorides, perchlorates, and nitrates. Thus, in effect, we consider the Gibbs energy and its temperature and pressure derivatives. The parameters obtained are useful for various thermodynamic calculations and will be especially valuable for mixtures where the other components have been treated in the same system.

The equations for activity and osmotic coefficients and for enthalpies have been published.[7] For the volumetric properties the derivation is similar to that for enthalpy, but the measured property is the density rather than the heat of dilution, and this yields the absolute rather than the relative apparent molal volume. The additional term, the partial molal volume of the solute at infinite dilution V^o, must be evaluated. One has, then,

$$\phi V = \bar{V}^o + \nu|z_M z_X|(A_V/3b)\ \ln(1+bI^{1/2}) - 2\nu_M\nu_X\ RT(mB^V_{MX} + m^2\ C^V_{MX}) \qquad (1)$$

where

$$B^V_{MX} = (\partial\beta^{(0)}_{MX}/\partial P)_{I,T} + (\partial\beta^{(1)}_{MX}/\partial P)_{I,T} \times (2/\alpha^2/I)\ [1-(1+\alpha I^{1/2})\ \exp(-\alpha I^{1/2})] \qquad (2)$$

$$C^V_{MX} = 1/2\ (\nu_M\nu_X)^{1/2}\ (\partial C^\phi_{MX}/\partial P)_{I,T} \qquad (3)$$

The density is related to the apparent molal volume by the expression

$$d = \frac{1000+M_2m}{(1000/d_o)+{}^\phi Vm}$$

where d_o is the density of the pure solvent and M_2 the molecular weight of the solute. The Debye-Hückel parameter for volume is

$$A_V = -3A_\phi\ RT[3(\partial\ln D/\partial P)_T + (\partial\ln V_w/\partial P)_T] \qquad (5)$$

where the last term is the negative of compressibility of the solvent. The equations for water which volume and the dielectric constant for water which were adopted earlier were used to calculate A_V. The value of A_V is 2.626 cc kg$^{1/2}$ mole$^{-1/2}$ for water at 25°C.

The specific parameters for each rare earth salt were evaluated by least squares from the original data of Spedding et al.[10] together with any other published data[11] which was judged to be of comparable accuracy. For the chlorides good fits were obtained up to the highest concentrations, frequently saturation. For the perchlorates and especially for the nitrates, it was possible to get good fits only up to about 2 M and the final calculations were based only on data up to this maximum molality for these salts.

The details of this evaluation process and the resulting tables of parameters are available in LBL Report 6399 and will be published soon.

It is interesting to note the magnitude of the temperature and pressure derivatives in relation to the parent functions. For the important parameter 3/2 $\beta^{(0)}$, which is of the order of unity, the temperature derivative is less than 0.0004 K^{-1}. Consequently, a 25° change in temperature causes less than 1% change in $\beta^{(0)}$ or 2% change in γ at 1 M. The pressure derivative is less than 0.00006 atm^{-1}; hence a 160 atm change causes less than 1% change in $\beta^{(0)}$. The Debye-Hückel coefficient is somewhat more sensitive to temperature, with 25° causing a 4% change, but is even less sensitive to pressure. Thus, the properties of these solutions do not change rapidly with temperature or pressure, and the dominant effect is the change of Debye-Hückel parameter with temperature.

In the full report (LBL-6399) and in our MMRD progress report the conclusions of interest to chemical theory at the molecular level are discussed. This research was supported, in part, also by the MMRD program at LBL.

PLANS FOR 1978

In the modeling work for next year our first attention will be given to estimates from the limited data now available for the effects on brine properties of the secondary constituents in typical geothermal brines. We hope also to complete work on sodium chloride at pressures in excess of the saturation curve and to develop a model for NaCl on a constant volume basis. This would be very useful as a basis for extrapolation to even higher temperatures and pressures.

The experimental program will give first priority to the development of the flow calorimeter into a successfully operating unit and to the measurement of heat capacities of brine components and thereafter of typical brines.

As time allows we expect to extend our program into problems in equilibria of solids with aqueous phases. Examples of geochemical interest will be chosen.

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SELECTED ALBITES AS CANDIDATES FOR HYDROTHERMAL SOLUBILITY MEASUREMENTS

J. A. Apps and J. M. Neil

INTRODUCTION

Ground waters contain many dissolved chemical components that result from reactions between mineral phases and the aqueous phase. In spite of the large effort which has gone into the study of these reactions little is yet known of either the equilibrium thermodynamic relations or the reaction kinetics between water and even the most common rock-forming minerals. Such information is required in order to interpret the physical and chemical changes that can take place in aquifers during ground water migration. In particular the problems of exploiting geothermal energy from liquid dominated reservoirs, ground water migration in formations adjacent to nuclear waste storage repositories, and chemical reactions involving the leaching or precipitation of toxic metals from solution all require an understanding of the thermodynamics and the kinetics of rock-water interactions.

The first part of our study will involve the measurement of the equilibrium solubility of albite, $NaAlSi_3O_8$, between 25°C and 400°C in sodium chloride solutions of varying ionic strength. Albite is a common rock forming mineral that is found in a wide range of geological environments. However, albites vary both in composition and in the degree of order in their aluminum silicate lattices. The compositional and structural variability result in significant changes in the thermodynamic properties; so the albite chosen for this study should be well characterized in terms of its chemical composition and structural state. Ideally, the sample should be chemically pure and well ordered.

This report describes our efforts to identify a well ordered low albite which would be obtainable in sufficient quantities for our experimental program.

SAMPLE DESCRIPTION AND CHARACTERIZATION

Six different albites were purchased from three mineral supply houses, and one albite was collected from the Franciscan formation in northern California. The sample descriptions are summarized in Table 1.

Moonstone is defined as a semitransparent, opaline lustered, adularia; however, the term is also used for opalescent plagioclase (especially albite). For this reason, sample AB-006 was purchased for analysis.

A potential, local source of high purity material is the vein albite from the Franciscan exposure at Tiburon. However, these veins are not widespread or persistent enough to make it feasible to collect sufficient material for our experimental program. Following a suggestion by R. Coleman, USGS, a large sample of albite was collected from veins in a monolith of glaucophane schist located near Cazadero, California.

Clean and mineralogically pure fragments of albite from each of these samples were prepared for chemical analysis using the procedure described by Hebert and Street.[1] Special care was taken to avoid sodium and potassium loss during the fusion stage. The analyses were made with a non-dispersive x-ray fluorescence spectrometer especially designed for light element measurements. The data

Table 1. Source and description of possible albite starting material.

Sample number	Description	Sample source and supplier
AB-001	Albite, variety Cleavelandite	Bob Ingersoll Mine, Keystone, South Dakota, Minerals Unlimited
AB-002	Albite with biotite	Dungannon Township, Ontario, Canada, Minerals Unlimited
AB-003	Albite	Custer, South Dakota, David New - Minerals
AB-004	Albite	Near Keystone, South Dakota Wards Natural Science Establishment
AB-005	Albite	50 miles SE of Virginia City, Madison County, Montana, Minerals Unlimited
AB-006	Moonstone	India, David New - Minerals
AB-007	Albite, veins from tectonic blocks in the Franciscan Formation	Cazadero, California, collected from location

from 2-minute runs were reduced by a computer code which made absorption and background corrections. The results are reported in Table 2. The samples were compared with a standard made from a mixture of the USGS standards, APG, and PCC, and against USGS standard G2. Errors are reported as the simple root-mean square deviation.

Table 3 shows the results listed in Table 2 recalculated as the number of atoms in a feldspar molecule with 32 oxygen atoms. All elements that are reported in Table 2 as being below a limit of accurate determination are not used in the calculations. The iron is assumed to be in the +2 state and to substitute for Ca in the M site,

Table 2. Provisional chemical analyses for albite (reported as weight percent oxide).

	Sample number[a]						
	AB-001	AB-002	AB-003	AB-004	AB-005	AB-006	AB-007
Na_2O	10.6±0.4	11.4±0.3	11.0±0.2	11.3±0.2	10.3±0.2	3.4±0.2	9.7±0.2
MgO	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Al_2O_3	19.7±0.2	24.5±0.2	19.6±0.2	19.8±0.2	19.5±0.2	19.1±0.2	18.7±0.2
SiO_2	66.8±0.4	58.1±0.4	68.1±0.4	67.9±0.4	67.2±0.3	62.6±0.4	62.8±0.4
K_2O	0.28±0.02	1.94±0.04	0.05±0.01	0.15±0.04	0.79±0.02	10.8±0.2	<0.03
CaO	0.43±0.02	1.78±0.03	0.29±0.01	0.20±0.03	0.85±0.03	0.38±0.03	1.11±0.03
TiO_2	<0.02	<0.04	<0.03	<0.02	<0.01	0.74±0.06	<0.02
Cr_2O_3	<0.02	<0.02	±0.01	<0.01	<0.01	<0.01	<0.01
MnO	<0.02	<0.02	±0.02	<0.02	<0.01	<0.02	<0.02
FeO	0.11±0.03	0.07±0.02	0.07±0.01	.02±0.01	0.48±0.02	0.03±0.02	0.03±0.02
Total	97.92	97.79	99.11	99.37	99.12	97.05	92.34

[a] Samples are described in Table 1.

Table 3. Number of atoms in a feldspar molecule on the basis of 32 oxygen atoms $[Na,K,Ca(Fe)](Al_4Si(Ti)_{12})O_{32}$.

	Ab-001	Ab-002	Ab-003	Ab-004	Ab-005	Ab-006	Ab-007	Amelia albite[a]
Na	3.665	4.070	3.428	3.851	3.544	1.235	3.555	3.963
Mg	-	-	-	-	-	-	-	-
Al	4.141	5.317	4.085	4.100	4.078	4.213	4.164	3.996
Si	11.914	10.701	12.044	11.935	11.926	11.716	11.872	11.989
K	0.062	0.454	0.011	0.032	0.179	2.577	-	0.096
Ca	0.081	0.351	0.054	0.056	0.162	0.076	0.219	-
Ti	-	-	-	-	-	0.130	-	-
Cr	-	-	-	-	-	-	-	-
Mn	-	-	-	-	-	-	-	-
Fe	0.016	0.010	0.010	0.002	0.008	0.005	0.005	-
X	3.824	4.885	3.503	3.941	3.893	3.893	3.779	4.06
Z	16.055	16.018	16.129	16.035	16.004	16.059	16.035	15.99
mole % Ab	95.84	83.32	97.86	97.72	91.04	31.72	94.07	97.6
Mole % An	2.54	7.39	1.83	0.81	4.37	66.20	5.93	-
mole % Or	1.62	9.29	0.31	1.47	4.60	2.08	-	2.4

[a] Analysis from Deer, Howie and Zussman.[4]

while the titanium is assumed to substitute for the silicon in one of the T sites. One of the analyses reported by Deer, Howie, and Zussman[2] for the Amelia Court albite is included for comparison. According to Deer, Howie, and Zussman, a criterion of analytical accuracy is that the sum of the atoms in the M site should be 4±0.1, and the sum of the atoms in the T site should be 16±0.1.

STRUCTURAL STUDIES

X-ray powder patterns of the albite samples were obtained using a 114.6-mm Debye-Scherrer diffraction camera with silicon metal as an internal standard. The films were read on a standard light table, and the least-squares refinement code by C.W. Burnham was used to refine the data. Table 4 lists the refined values of both the direct and reciprocal lattice constants as well as the various structural parameters which can be determined from cell constants. The cell parameters used by Borg and Smith[3] to generate a theoretical powder pattern are also included for a comparison.

CONCLUSIONS

Three of the five albites examined (Ab-001, Ab-003 and Ab-004) appear to possess the required degree of purity for our hydrothermal solubility measurements. Ab-002 and Ab-007 have unacceptably high concentrations of calcium and potassium. However, the calcium in Ab-007 may be due to zoisite contamination. Final choice of a suitable sample will be made after further optical and transmission electron microscope studies. An x-ray structure determination will be made on the selected albite to verify that it is ordered, and therefore a low albite.

Table 4. Crystallographic parameters of albites.

	Ab-001	Ab-002	Ab-003	Ab-004	Ab-005	Ab-006[a]	Ab- 007	Ab Standard[b]	maximum microcline[b]
A* (Å-1)	0.1374	0.1373	0.1377	0.1377	0.1373	0.1301	0.1375	0.1374	0.1299
B*	0.0786	0.0785	0.0784	0.0781	0.0783	0.0772	0.0783	0.0784	0.0772
C*	0.1565	0.1566	0.1567	0.1566	0.1568	0.1534	0.1566	0.1566	0.1539
α* (deg)	86.2986	86.4026	86.4100	86.3047	86.3878	90.3926	86.2817	86.3326	90.441
β*	63.5604	63.5573	63.4877	63.4501	63.5070	64.1537	63.4641	63.5227	64.170
γ*	90.6050	90.4403	90.5799	90.3544	90.4162	92.0488	90.4269	90.4646	92.262
A (Å)	8.1371	8.1417	8.1249	8.1268	8.1463	8.5494	8.1345	8.138	8.560
B	12.7603	12.7816	12.7929	12.8372	12.8069	12.9700	12.0872	12.789	12.964
C	7.1558	7.1493	7.1536	7.1603	7.1452	7.2205	7.1586	7.156	7.215
α (deg)	94.4364	94.2380	94.3027	94.3092	94.2447	90.5564	94.3707	94.33	90.605
β	116.5444	116.5307	116.6106	116.6357	116.5799	115.8491	116.6280	116.570	115.833
γ	87.4789	87.7151	87.5567	87.7534	87.7306	87.9136	87.6617	87.65	87.70
volume cubic cell (Å^3)	662.6456	663.7989	662.8836	665.8311	664.8216	720.0475	664.7321		

[a] Ab-006 indexed on maximum microcline.
[b] Data from Borg and Smith.[3]

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THERMODYNAMIC PROPERTIES OF SILICATE MATERIALS

I. S. E. Carmichael, S. A. Nelson, and L. Moret

INTRODUCTION

The crust of the earth, in particular that under the oceans, is made up of basaltic lavas, which before crystallizing or congealing, were silicate liquids of rather variable and complex composition. Generally speaking, they are made up of eight major oxide components--SiO_2, TiO_2, Al_2O_3, FeO, MgO, CaO, Na_2O and K_2O--so that any experimental investigation of the properties of silicate liquids of relevance to nature must be designed to measure the partial molar quantities. Despite the very great importance of natural silicate liquids to many phenomena in the earth (volcanoes, geothermal localities, ore-bodies of certain types), there is surprisingly little experimental data available on their properties, presumably because of the high temperatures involved (1000° - $1500^{\circ}C$). Last year an essential start was made on measuring the heat capacities (Cp) of silicate liquids in the temperature range 1200° - $1650^{\circ}K$[1] and their derived partial molar quantities, which are independent of temperature within experimental error. This study also considered the ascent of basaltic magma, for in many cases what we observe on the surface has been determined as much by the ascent pattern as by the conditions of the source region in the earth's mantle.

ACTIVITIES IN 1977

An apparatus, comprising an electronic balance and vertical furnace, has been constructed to measure the density of a variety of silicate liquids using the Archimedes principle. After thorough testing of thermal stability, operational ease, and calibration, the first measurements are at hand on one silicate liquid. The apparatus will be used to determine density, and its temperature dependence, of a wide variety of silicate liquids, so that the partial molar volumes and expansivities can be obtained; this will allow the data to be extended to natural silicate liquids of all types.

Many silicate liquids, when cooled quickly, form a glass, metastable with respect to crystals, but each with its own reproducible and unique properties. In solids, Al undergoes a change in co-ordination with oxygen at high pressure, for in $NaAlSi_3O_8$ crystals it is tetrahedrally co-ordinated, but in high pressure $NaAlSi_2O_6$, it is octahedrally co-ordinated. The same effect should be present in liquid $NaAlSi_3O_8$, and a number of samples were quenched to a glass from $1500^{\circ}C$ and in the pressure range 1-60 kbars. One way in which this co-ordination change could be manifested is in the heat capacity at moderate temperatures (to avoid annealing), for the heat capacity of Al_2O_3 in sixfold co-ordination is greater than in four-fold co-ordination. Our preliminary results so far show that change in Cp with pressure decreases up to 40-50 kbars, but that the 60-kbar sample has a larger Cp than the 1-bar sample.

The common mineral quartz, SiO_2, undergoes a transformation near $848^{\circ}K$ with an enthalpy change of approximately 290 cal/mole. It has been known for 20 years that the inversion temperature varies with the temperatures of growth, but no data were available at that time on the latter. We have collected quartz crystals from a wide range of known temperatures of growth, both natural and synthetic, and it appears that the α-β inversion temperature is indeed inversely proportional to the growth temperature; this is probably due to solid solution of Na, etc. We have found that there is a very good correlation between the inversion temperature, the volume of the unit-cell (which decreases slightly with increase in foreign ions in solution), and the growth temperature. It appears that easily measurable properties of quartz, particularly that grown above $848^{\circ}K$, may be used as a geothermometer.

PLANNED ACTIVITIES FOR 1978

In addition to continuing the density measurements, an apparatus has been designed and partially built to determine the sound wave velocity in silicate liquids. The intention is to determine the adiabatic compressibility of silicate liquids, and its temperature dependence, on the same compositions as have been used for density measurements. Eventually we hope to obtain partial molar compressibilities (isothermal), their temperature dependence, which together with the volume data should allow a complete description, apart from co-ordination change effects, of the volume of all varieties of natural silicate liquids in the P-T field in which they occur. As a successor to the study of heat capacities, we intend to study other compositions in order to obtain partial molar heat contents in the liquid state. It is anticipated that about 20 compositions will be analyzed by neutron activation to determine the major components in order to check the effect of foreign ions on the properties of natural quartz.

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STUDIES OF MAGMATIC MATERIALS

F. Asaro and H. V. Michel

INTRODUCTION

The purpose of this study is the adaptation of high precision techniques of chemical measurement to problems in geochemistry, geothermal studies, and problems relevant to storage of nuclear wastes. It should permit more accurate determinations of the thermodynamic quantities such as distribution coefficients of elements between lava melts and crystals and also offer new ways of measuring temperatures of lava chambers.

The project started on a rather small scale in 1973 and has undergone considerable modification since then.

In the prior years many lavas and crystal inclusions had been measured by neutron activation analysis for about 30 trace, minor, and major elements. Although lava measurements were reliable, crystallized material from the lava and specific minerals separated from the lavas or nodules in them appeared to contain extraneous inclusions or impurities.

1977 ACTIVITIES

In this last year, separation techniques in use on the U.C. Berkeley campus have resulted in purer samples of crystals and mineral separates. Measurement techniques of neutron activation analysis along with better sample preparation techniques improved to the extent that differences in chemical abundances due to fractionation of minerals within a sample bottle are obvious.

In the neutron activation process material of unknown composition is placed in a neutron flux, and the neutrons cause stable isotopes of the various elements in the unknown to transform to excited or radioactive species. Many of these species or their radioactive daughter products will have characteristic radiations, usually gamma rays, which can be measured subsequent to the irradiation. The amounts of the different elements are determined by comparison with amounts of characteristic radiations emitted by standards of known composition. The precision and accuracy of measurement depend on the care with which irradiation conditions are controlled and calibrated. They also particularly depend on the care with which the gamma ray spectral measurements are made. Generally precise determinations necessitate: irradiation and measurement of standards and unknowns in the same configuration; selection of appropriate gamma rays for study and removal of spectral interferences with these gamma rays; and determination of losses of data in counting equipment as a function of counting rate. In addition, if a small part of a sample is removed for analysis, then the sample must be more homogeneous in the abundances of the elements of interest than their precision of measurement. Otherwise the precision is wasted.

Table 1 shows the abundances of four of the most precisely measured elements in a basalt analyzed by neutron activation methods described above. Also shown are measurements by x-ray fluorescence and wet chemical methods. Included in the table are the estimated (1 standard deviation) errors. The agreement is consistent with the errors. Thus the uncertainties in the neutron activation measurements are about 1% or less for elements shown. In addition, three different techniques give the same answer when the work is carefully done. This neutron activation analysis is part of a measurement system in which about 50 elements are searched for by INAA, about 40 are usually detected in materials with compositions similar to the earth's crust, and about 30 are measured with good precision.

Table 1. Basalt abundances as measured by different techniques.

	Basalt abundances, %		
Element	Neutron activation analysis	Wet chemistry[a]	X-ray fluorescence[b]
Na	2.34 ± 0.015		2.35 ± 0.04
Fe	9.67 ± 0.08	9.69 ± 0.06	9.76 ± 0.12
Al	7.16 ± 0.08		7.27 ± 0.04
Ti	1.65 ± 0.02	1.64 ± 0.02	1.57 ± 0.05

[a] I.S.E. Carmichael
[b] H.R. Bowman and R.D. Giauque

The precision of trace element measurement can be evaluated by comparison of neutron activation results from different laboratories on nearly identical samples. Table 2 shows a comparison of the measurements by the Hebrew University of Jerusalem and the Lawrence Berkeley Laboratory.[1] The abundances of three elements - Eu, Sc, and Ta - in samples of a fired clay and rhyolite (a siliceous material erupted in the later stages of volcanism) are tested in Table 3. The agreement is excellent from one point of view as the two laboratories agree within about 3% on elements with abundances of the order of 1 ppm.

From another point of view the agreement is not perfect. The errors due to counting radioactivity (1 standard deviaiton values) are also included in Table 2, and the two values for scandium differ by nearly 6 standard deviations for the rhyolite. Although this might be due to actual differences in composition between different

Table 2. Trace element abundances as measured at different laboratories by neutron activation analysis.

Element	Abundances, ppm Fired Clay	Rhyolite	Laboratory
Eu	1.468 ± 0.022	0.045 ± 0.007	H.U.[a]
	1.498 ± 0.013	0.047 ± 0.005	LBL[b]
Sc	20.08 ± 0.04	3.049 ± 0.012	H.U.[a]
	20.10 ± 0.06	2.954 ± 0.013	LBL[b]
Ta	1.336 ± 0.024	2.055 ± 0.033	H.U.[a]
	1.33 ± 0.01	2.01 ± 0.01	LBL[b]

[a] Hebrew University (see Ref. 1)
[b] Lawrence Berkeley Laboratory (see Ref. 1)

Table 3. Precision of neutron activation analysis from six nearly identical samples.

	RMSD, %	Standard deviation of counting error, %	Procedural uncertainty, %
Sm	0.23	0.14	0.18
	0.27	0.09	0.26
Sc	0.30	0.20	0.22
	0.26	0.20	0.17
Mn	0.33	0.29	0.16
Ce	0.51	0.33	0.39
Fe	0.58	0.43	0.39
	0.57	0.37	0.43
Eu	0.49	0.43	0.23
Ta	0.56	0.49	0.27
Average	0.41		0.27

splits of the rhyolite, it seems more probable that one or both institutions are making a small error in their scandium measurements. Table 3 shows a limit on the precision of measurements made at our laboratory. The root-mean-square deviations for the 10 most precisely measured radiations in six samples is 0.41%. If the standard deviations due to uncertainties in counting gamma rays are removed, the average remaining uncertainty is 0.27%. Although this may be due in part to actual variations in abundances in the six samples, it seems most likely to be due to unknown problems in the Berkeley measurement system. By cross-checking measurements with other techniques and laboratories we hope to approach 0.27% as our actual precision for the best measured elements.

It is worth noting that unless care is exercised in the selection and preparation of samples, one portion of a roughly ground rock sample may have a much different abundance for some elements than an adjacent portion.

Next, applications of neutron activation analysis to problems in geology will be considered. In the northwest United States in the region of the Columbia River Plateau, basalt flows have been ejected periodically over many millions of years. They have formed layers that total several thousand feet in depth; each layer is somewhat homogeneous chemically. Such basalts are considered as possible repositories for commercial radioactive wastes.[2] In studies aimed at determining the feasibility of each storage, the ability to make a positive identification of a sample (of a drill core) with a specific flow is useful. The major elements have been used with some success for this purpose. Even the inclusion of a few trace elements, however, makes the assignments more definitive as will be shown next.

The Atlantic Richfield Hanford Company (ARHCO), which has now become Rockwell Hanford Operations, sampled the Columbia River Plateau basalts in a number of reference areas.[2] The samples were chemically analyzed by atomic absorption and usually by neutron activation. These data were used to form reference groups of known flows. Each flow was designated by a mean value and a standard deviation for each element considered. ARHCO had in addition drilled several boreholes into the Plateau basalts and sampled the cores about every 20 or 30 ft. The core samples were analyzed in the same way as the reference samples but fewer neutron activation analyses were made.

The correlations of about 80 samples from one of these boreholes (DH-5)[3] are shown in Figure 1 with each of the nine reference flows. The abscissa is the depth from which the samples were taken and the nine ordinates are the correlation values. These values equal $1.5 - \sqrt{chi^2/(n-2)}$ where chi^2 has its conventional meaning and is summed over n-1 elements. The element whose abundance agrees the poorest is rejected. The lowest value of the correlation is taken as 0. In Figure 1, data which include neutron activation analysis for four trace elements as well as atomic absorption measurements on nine major and minor elements are represented by dots. Atomic absorption data alone are represented by x's. There are three prominent correlations in the top 600 ft but also a few ambiguities. Many of the correlations below 700 ft would probably be reduced with high precision trace element analyses on both reference and borehole samples.

The effect of trace element measurements on a much greater proportion of the samples is indicated in Figure 2 which shows data from another borehole, DDH-3. There were no ambiguities in these data for the first 1100 ft. In fact, all of that data can be compressed into one graph. As seen in Figure 2, there are four distinct flows with no overlap. The probability of an error in assignment to one of the flows (Pomona) was calculated to be less than 1 in 10^{10} with certain restrictive assumptions. Lower flows, even with four trace elements measured, have many ambiguities as seen in Figure 3. It is possible that these data could be correlated much more definitively if a much larger number of trace elements were used in the analysis.

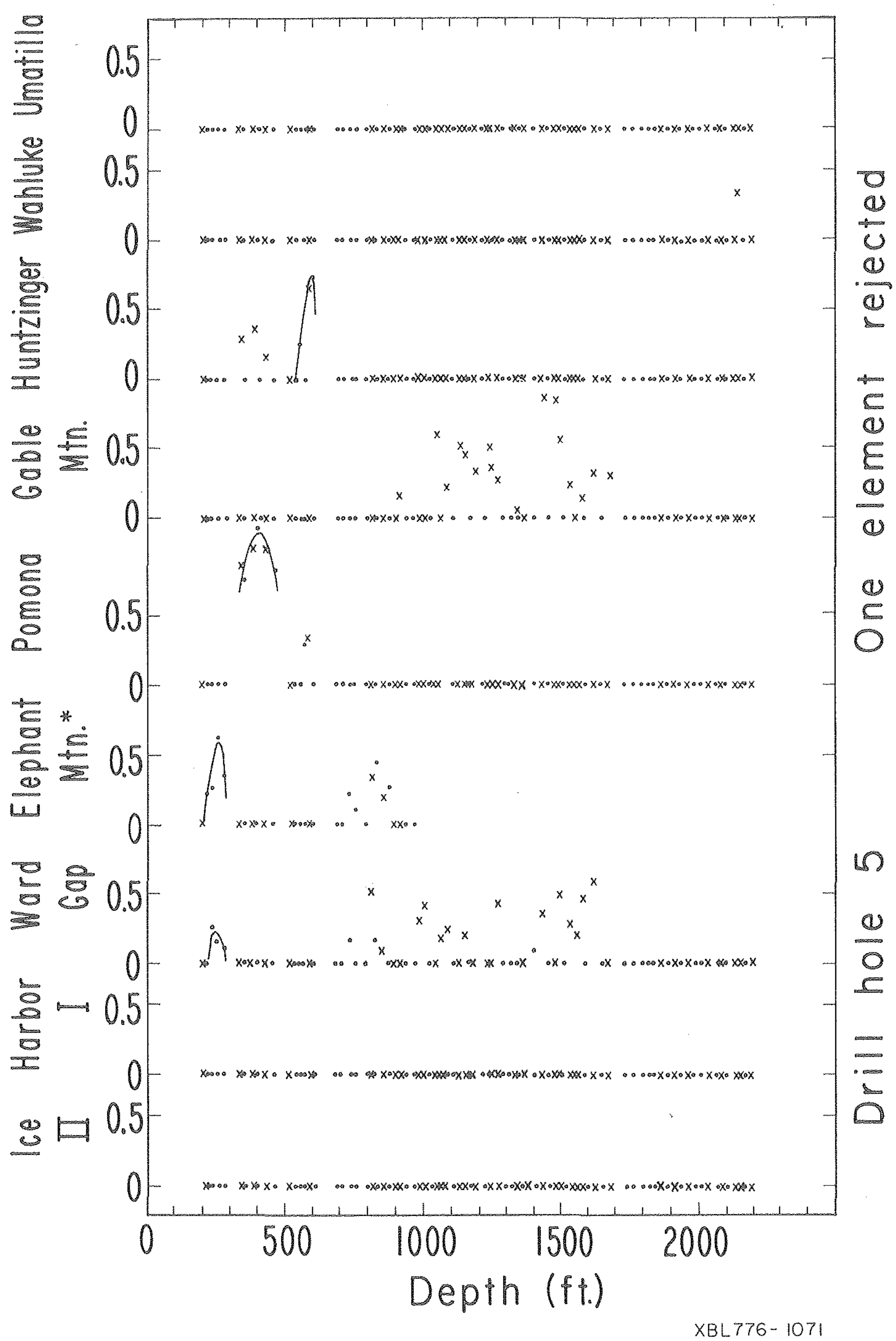

Figure 1. Correlation diagrams for rock samples from upper part of borehole DH - 5. Data points indicated by "x" - eight major elements and one minor element (Ba) included in the correlation. Data points indicated by "•" - an additional four trace elements (Cr, Eu, Sc, and Co) included in the correlation.

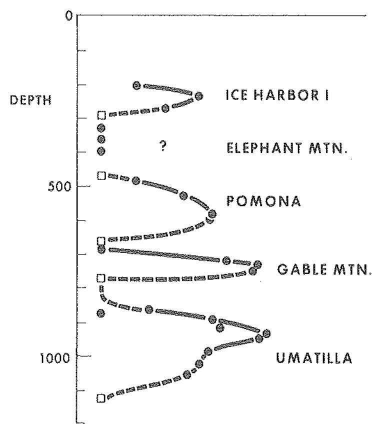

Figure 2. Correlation diagram for rock samples from upper part of borehole DDH - 3. Data points indicated by "●" - 13 major, minor, and trace elements included in the correlation. Data points indicated by "□" - correlations are so small samples are not basalts.

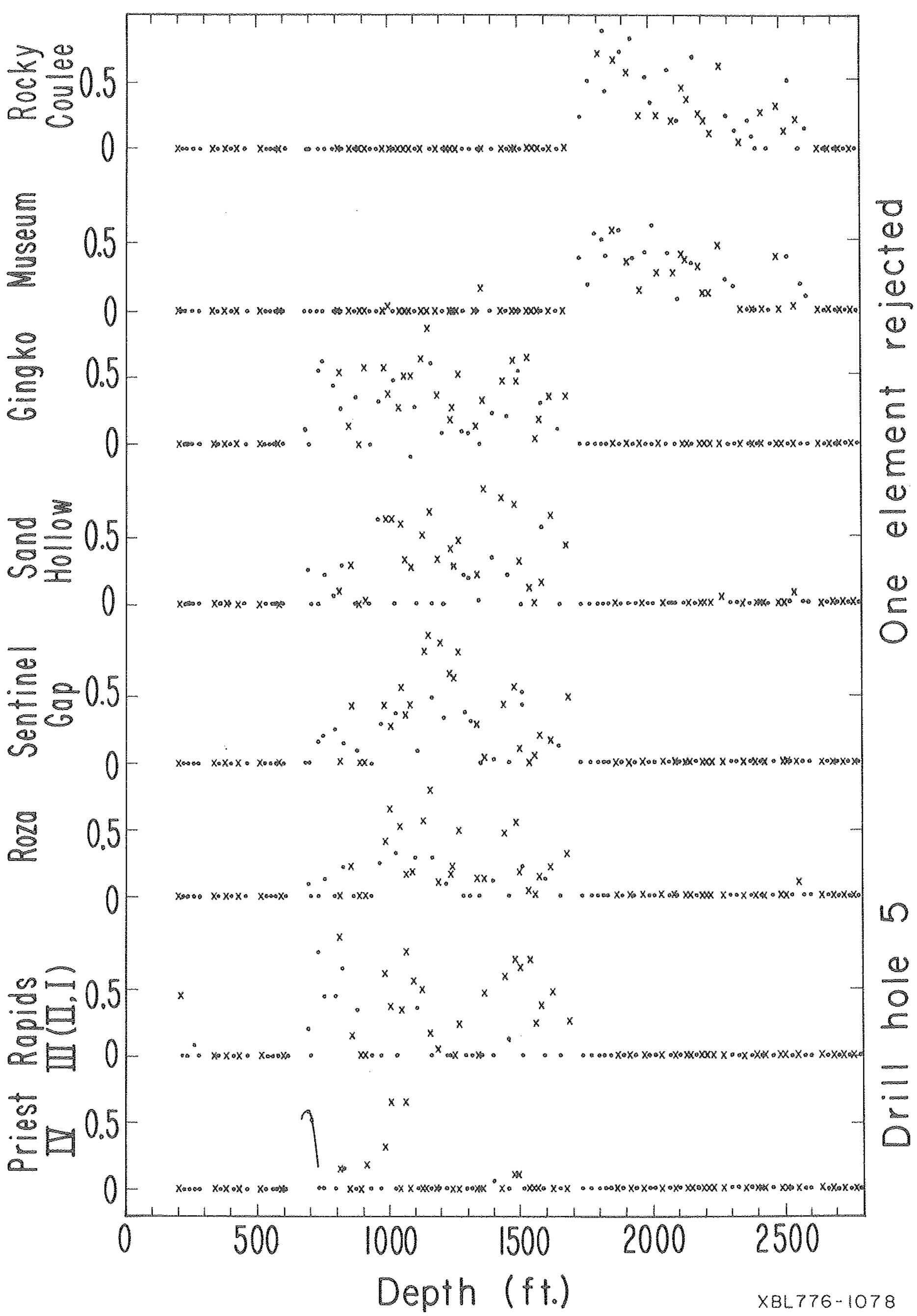

Figure 3. Correlation diagrams for rock samples from middle part of borehole DH - 5. The meaning of the symbols is the same as in Figure 1.

The measurement methods studied here apply to fossil fuel studies (raw and spent oil shales and oily waters), studies of distribution of trace elements in aquifer systems, and fingerprinting of rhyolites for stratigraphic dating (in collaboration with the U.S.G.S.).

Next year the effect of sample fractionation between sampling and measurement will be studied. High precision measurement techniques will be applied to fingerprinting of basalts to determine if different flows can be better distinguished by these methods.

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IN-SITU STRESS MEASUREMENTS

T. V. McEvilly and J. Wang

INTRODUCTION

In laboratory experiments, changes in the state of stress of rocks typical of crustal composition produce measurable changes in elastic properties. It follows that a technique for precise measurement, in situ, of changes in elastic properties of crustal rocks would have potential in monitoring subsurface stress changes. Clearly, applications exist in the areas of geothermal reservoir changes, underground waste disposal effects, dam-induced seismicity, earthquake risk at critical facility sites, and in other less spectacular subsurface processes. By 1974, using seismic waves from earthquakes and explosions, seismologists had demonstrated a capability to detect changes greater than about 10^{-2} in average velocity along a "path of convenience," that is, a source-to-receiver path of undetermined geometry. However, the available precision was insufficient for detecting changes in average velocity over a small zone at depth despite attempts to do so by changing source and receiver locations.

It was clear that precision and stability of measurement had to be improved by 1 to 2 orders of magnitude, and that the best possible system would be based on current seismic reflection technology developed for petroleum prospecting. With support from Continental Oil Company (Conoco), the U.S. Geological Survey, and LBL, a special purpose VIBROSEIS (tradename, Conoco) programmable seismic wave source and recording system was fabricated to test the feasibility of precise velocity monitoring using travel-time of reflections from deep discontinuities within the earth's crust. Initial tests in 1976 were very encouraging.

1977 RESULTS

System stability better than 10^{-4} was verified and indications were obtained that tidal stresses (<0.1 bar), as well as shallow stress changes (<1 bar) accompanying creep events on the San Andreas fault, produced detectable changes in velocities. Considerable time was spent in studies of instability sources and methods to eliminate them, so that a long-term accuracy of 10^{-4} can be maintained. The concept as well as the special two-man field system have proved very successful.

PLANS FOR 1978

Research will continue in 1978, but the program support will come from the U.S. Geological Survey, under the Earthquake Prediction Program, directly to the Seismographic Station, Department of Geology and Geophysics, University of California, Berkeley. Routine measurements are being planned to measure and study velocity changes in regard to earthquake prediction.

VISCOSITY OF AQUEOUS SODIUM CHLORIDE SOLUTIONS FROM 0°C TO 150°C

H. Ozbek and S. L. Phillips

INTRODUCTION

The purpose of the National Geothermal Information Resource (GRID) is mainly to compile and evaluate basic data on geothermal energy for electrical and nonelectrical uses. While the larger work covers a number of areas, this report is limited to a critical evaluation of data on the viscosity of sodium chloride solutions at elevated temperatures, pressures, and saturation concentrations. The objective is establishing a databank of published data on basic energy properties of aqueous NaCl solutions covering the ranges of geothermal interest: temperatures to 350°C, pressures to 50 MPa (500 bars), and concentrations to saturation. The present work gives the results of a survey and evaluations of a subset of this databank: that dealing with the viscosity of sodium chloride solutions.

The literature screened in compiling the viscosity data covers the period from 1929 to 1977; data obtained prior to 1929 are contained in the International Critical Tables for NaCl solutions at atmospheric pressure over the temperature range 0°C to 100°C, and concentrations from 0 molal to 5 molal. From 1929 to 1977, researchers generated viscosity data for temperatures to 150°C, pressures to 30 MPa, and concentrations to saturation.

ACCOMPLISHMENTS IN FISCAL YEAR 1977: EVALUATION AND CORRELATION

A comprehensive search of the published literature for NaCl viscosity data was made, and all available copies of the original publications were assembled using the following main sources for literature references: (1) the Department of Energy Technical Information Center's RECON System, which includes the Energy Data Base and Water Resources Abstracts; (2) the International Critical Tables; and (3) relevant journals and reports.

The data selected for correlation are reported experimental values, and do not include either smoothed or calculated data.[2] All data in this table have been converted where necessary to the ^{12}C scale of atomic weights, to the g/cm^3 basis for density, to centipoise for viscosity, from molar to molal concentrations, and from relative to absolute viscosity values. The needed water viscosity data were taken from the results of the Eighth International Conference on the Properties of Steam.

The following statistical equation was developed from the experimental data:

$$\eta = c_1 + c_2 \exp(\alpha_1 T) + c_3 \exp(\alpha_2 m) + c_4 \exp[\alpha_3(0.01T + m)] + c_5 \exp[\alpha_4(0.01T - m)] \quad (1)$$

where

η = viscosity, cp

T = temperature, °C

m = concentration, molality

c_1 = 0.1256735 α_1 = -0.04296718

c_2 = 1.265347 α_2 = 0.3710073

c_3 = -1.105369 α_3 = 0.4230889

c_4 = 0.2044679 α_4 = -0.3259828

c_5 = 1.308779

Equation (1) is valid only to pressures of 30 MPa and at temperatures to 150°C.

Figure 1 shows viscosity versus concentration, from Eq. (1), for selected temperatures between 0°C and 150°C. Figure 2 is a plot, based on Eq. (1), of viscosity versus temperature. Data may be interpolated with Eq. (1) to a standard deviation of 1.5% over the entire temperature, pressure, and concentration range (see Fig. 3). Table 1 contains smooth values of viscosity, calculated from Equation (1).

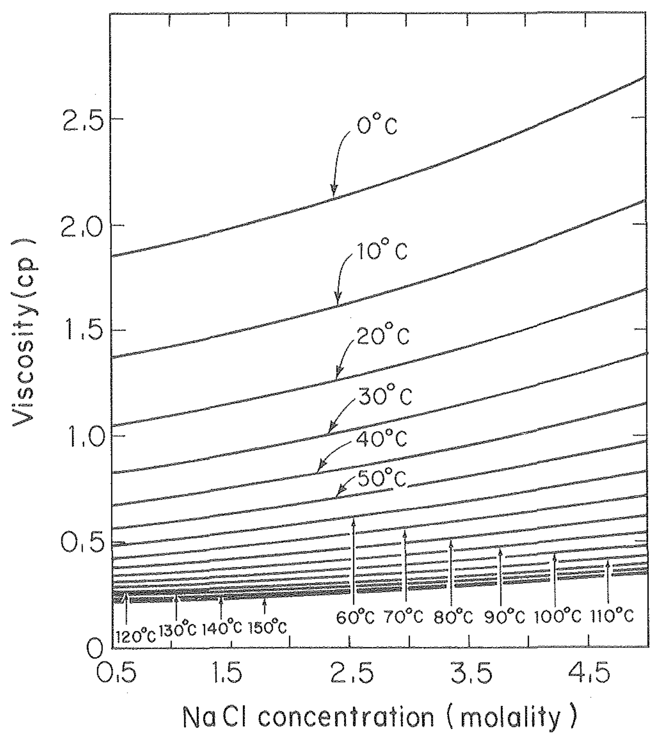
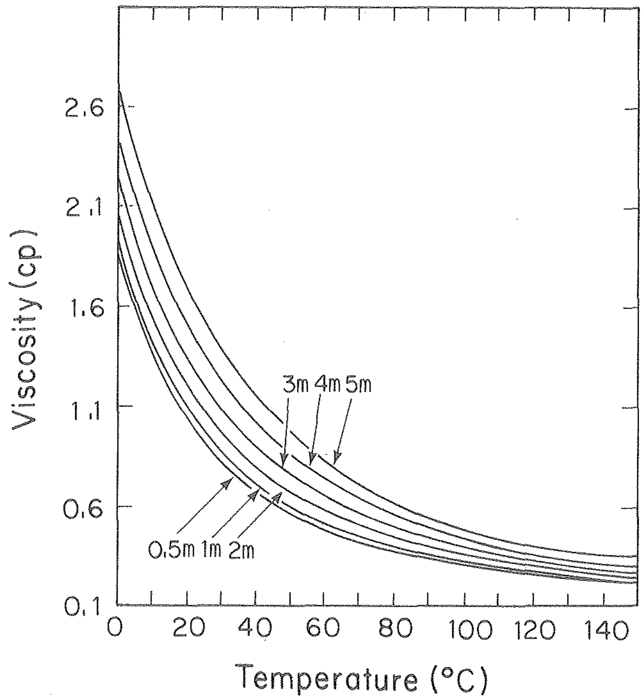
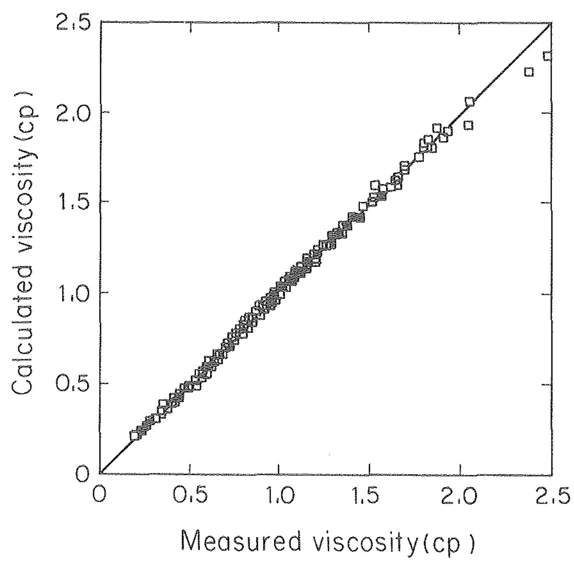


Figure 1. Viscosity of NaCl solutions versus concentration using Eq. (1).



XBL 783-518

Figure 2. Viscosity of NaCl solutions versus temperature using Eq. (1).



XBL 783-422

Figure 3. Comparison of calculated NaCl viscosity using Eq. (1) with measured values. Deviation for all values is 1.5%.

Table 1. Smooth values of the viscosity of NaCl solutions calculated from Eq. (1).

	Viscosity, cp					
m NaCl / °C	0.5	1.0	2.0	3.0	4.0	5.0
0	1.853	1.914	2.058	2.234	2.448	2.701
10.0	1.373	1.428	1.556	1.712	1.899	2.118
20.0	1.049	1.098	1.212	1.349	1.512	1.699
30.0	.827	.871	.972	1.092	1.232	1.391
40.0	.673	.712	.800	.905	1.024	1.158
50.0	.564	.598	.675	.765	.866	.978
60.0	.484	.513	.580	.657	.743	.835
70.0	.423	.449	.507	.572	.644	.719
80.0	.377	.399	.449	.504	.564	.626
90.0	.340	.359	.401	.448	.498	.549
100.0	.310	.326	.362	.401	.443	.487
110.0	.285	.299	.329	.363	.399	.439
120.0	.264	.276	.302	.331	.363	.402
130.0	.246	.256	.279	.305	.336	.376
140.0	.231	.240	.261	.285	.316	.361
150.0	.218	.227	.246	.270	.304	.357

SUMMARY AND CONCLUSIONS

The currently available experimental data on the viscosity of NaCl solutions is sparse and covers mainly pressures from atmospheric to 30 MPa (300 bars), concentrations to saturation, and temperatures to 150°C. A correlation equation was developed which reproduces the experimental data by 1.5% over the temperature range 0°C to 150°C. Additional laboratory measurements on the viscosity of NaCl solutions to 350°C and 500 bars are needed.

PLANNED ACTIVITIES FOR FISCAL YEAR 1978

Thermal conductivity data for aqueous sodium chloride solutions will be compiled and disseminated. Enthalpy data on sodium chloride solutions are expected to be critically evaluated, a correlation expression developed, and the result of this work disseminated as an LBL report. Other basic properties (e.g., free energy) would be compiled in the remainder of fiscal year 1978.

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IN-SITU LEACHING OF URANIUM ORES

J. W. Evans

A major portion of the effort expended on this topic was aimed at defining a suitable research program, submitting a request to ERDA for substantial funding, and completing the design of a prototype experimental rig for use in the investigation.

In situ leaching of uranium ore is now being practiced at approximately a dozen sites in south Texas, Wyoming, and Colorado. A leaching solution (usually ammonium carbonate/bicarbonate solutions plus hydrogen peroxide) is pumped into the underground ore body through several injection wells. The leaching solution passes through the ore body (typically a permeable sandstone deposit) oxidizing the uranium to the hexavalent form and thereby enabling it to pass into solution. The solution is pumped out of the ore body through recovery wells and treated on the surface (usually by ion exchange) to recover the uranium values.

Discussions were held with research and operating personnel of four companies (Intercontinental Energy Company, Anaconda, Mobil Oil, and Atlantic Richfield) involved in in situ leaching, as well as with U.S. Bureau of Mines and ERDA personnel most closely involved in this technology. A visit was paid to an operating mine (Pawnee Mine, ICE) and two conferences on this topic were attended (American Nuclear Congress, Golden, Colo., April 1977; and American Institute of Mining Metallurgical and Petroleum Engineers, Corpus Christi, Texas, September 1977).

A clearly defined problem encountered in the leaching operation is changes in permeability of the ore body which occur during leaching. Under some circumstances loss of permeability occurs and results in reduced productivity and/or higher pumping costs. The ore body must be "restored" after leaching. This entails removing residual leaching reagents remaining in the ore body by flushing with water or chemical solutions. Permeability loss prior to or during restoration would make this environmentally important step more difficult.

The circumstances under which permeability loss occurs are poorly understood, as is the reason for permeability loss. Hypotheses that have been put forward include blinding of pores by either evolved oxygen bubbles or transported fines, swelling of clay particles within the ores and alternative solution, then precipitation, of various species.

The research program that we are developing at Berkeley is aimed at determining under what conditions such permeability loss occurs and the cause of permeability loss. Similar work is being performed by Westinghouse research laboratories under contract to the U.S. Bureau of Mines. Our proposed experimental approach is similar except that it entails using smaller (and therefore more versatile) equipment. The emphasis will be on the fundamental causes of permeability loss while the Westinghouse contract places no obligation on their investigators to study the causes of the effects they observe.

A sketch of the prototype permeability rig is shown in Figure 1. Ore is to be crushed and

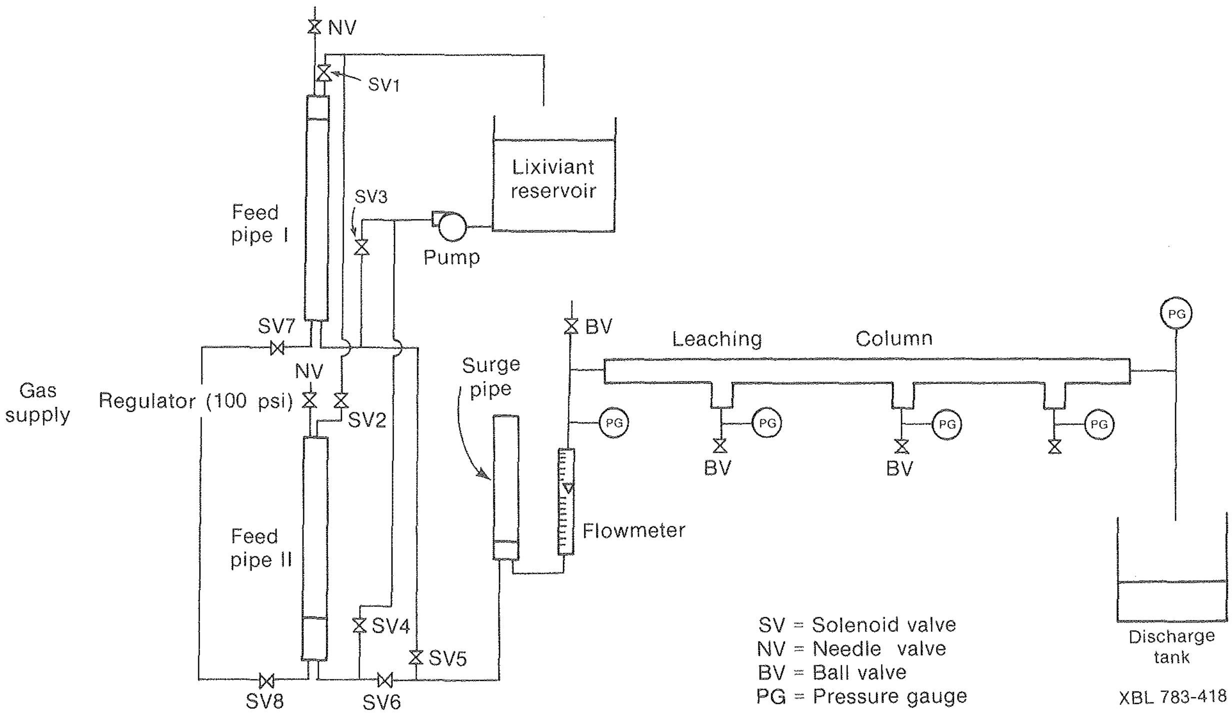

Figure 1. Permeability apparatus for in situ leaching investigation.

packed into Pyrex columns that are 2 in. in diameter and 12 ft long. Solutions will be driven by gas pressure through these columns from one of two 1-in. diameter pipes. A system of solenoid valves (SV) operated by a time switch enables one of the 1-in. columns to be filled by a pump from a reservoir tank while the other column is discharging. Pressure gauges at both ends and along the length of the ore column enable determination of the pressure profile along the column; together with measurement of the flow rate this enables determination of the permeability as a function of time.

A battery of tests (particle size determination, scanning microscopy, BET surface area measurement, etc.) can be used to examine the ore before and after permeability loss in an effort to determine the cause of the loss.

It is hoped that funding will be provided through the Grand Junction Office of the Department of Energy sometime in fiscal year 1978. In the meantime it is planned to build the prototype experimental permeability rig using Program Development Funds.

METHODS FOR DETERMINING THE EQUILIBRATION TEMPERATURES OF MAGMATIC CRYSTALLINE ASSEMBLAGES: TRACE METAL DISTRIBUTIONS

H. R. Bowman, I. S. E. Carmichael, and S. A. Nelson

INTRODUCTION

One of the more difficult tasks in geology is to estimate the temperature at which any crystals grew in a natural liquid, as in a rock, particularly if the crystal growth occurred in the range 750°-1300°C. Unfortunately, magmas show a compositional range, so that those which typically inhabit the 800°C range are quite different in composition from those which crystallize at higher temperatures. Therefore, there are two effects to be isolated, one due to the change in composition of the solid-solutions, and the other due to temperature.

1977 ACTIVITIES

We decided to make a preliminary investigation of the distribution of the rare-earth elements, as determined by neutron activation, between various crystals in lavas which crystallized over a wide temperature range. In Figure 1 the concentration of the elements in the solid phase divided by that in the liquid is shown for a number of rare-earth elements found in a variety of coexisting solid-solutions.

Clearly, the magnitude of the distribution coefficient, plotted on a logarithmic scale, increases with decreasing temperature, and indeed the pattern, or shape, of these curves also changes. By formulating these results as exchange equilibria, taken in conjunction with experimentally determined values of the equilibrium constant, it is possible to decipher the compositional dependence of the distribution of elements between crystals as the major components in the crystals change. This is of great importance in any attempt to unravel the equilibration temperatures of minerals in mantle fragments brought to the surface by volcanoes. Only in this way will it be possible to map the isotherms at depths up to 150 km, the region that has the greatest effect on the earth's surface and on those parts of the crust which are of economic and social importance.

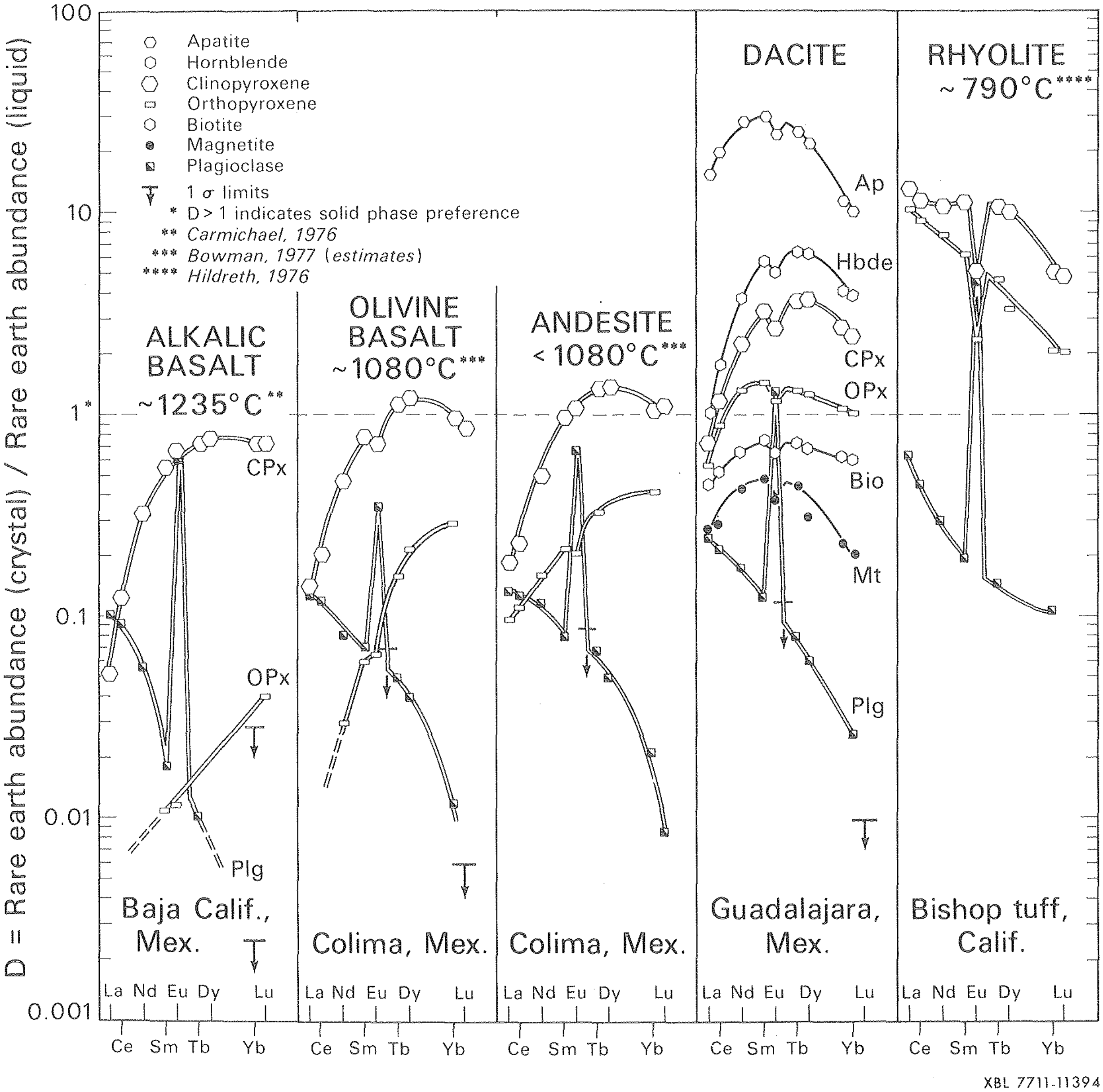

Figure 1. Neutron activation analysis: rare earth element distribution (D) between crystals and liquids for various lavas. Lava temperatures decrease from left to right.

ELECTROCHEMICAL STUDIES ON THE DISSOLUTION AND FLOTATION BEHAVIOR OF ORE-PYRITE AND COAL-PYRITE

D. W. Fuerstenau

INTRODUCTION

The necessity for the increased use of coal for energy has increased the interest in research on the desulfurization of coal as well. Thus far, the two most common methods used to deal with the problem of sulfur in coal are (1) flue gas desulfurization after combustion and (2) physical mineral beneficiation processes for separating mineral matter (ash and pyritic sulfur) from coal before combustion. The first method has the disadvantage that it creates the problem of disposal of spent sulfate slurries at the power plant site; in addition, there are other operational problems, such as corrosion and clogging of scrubbing towers. Sulfur removal at the mine site is interesting but the process is limited not only by the degree of liberation that can be obtained between coal and mineral phases by comminution, but also because the relatively fine particles produced cannot be readily handled. However, recent increased interest is being directed toward the desulfurization of coal by flotation or by leaching methods, and some of the new processes have been tried on a pilot plant scale. A study of the mineral/solution interface and the surface-chemical reactions taking place at this interface is important to further development of both leaching and flotation processes.

First of all, it is known that the mineral pyrite (the main inorganic sulfur-bearer in coal) is a semiconductor and hence some of the reactions occurring at the pyrite/aqueous interface are of an electrochemical nature. Therefore, investigation of the electrochemical nature of pyrite in aqueous systems of interest to the leaching and flotation of coal were undertaken. Some studies on the flotation of pyrite from coal have suggested that coal-pyrite behaves differently from ore-pyrite. Hence, in this brief research program, the electrochemical technique of linear-sweep voltammetry (LSV) was used to attempt to discern any difference between coal-pyrite and ore-pyrite.

EXPERIMENTAL METHODS AND MATERIALS

A single crystal of ore-pyrite and a hand-picked pyrite sample occurring near a coal seam were used for the study. The coal-pyrite has coal particles well interspersed within it, as observed by optical and scanning electron microscopy. The crystal structure of both samples was analyzed by x-ray diffraction methods and was confirmed to be that of pyrite. "Energy dispersion analysis by x-ray" (EDAX), and "electron microprobe analysis" both showed the chemical composition to be close to that of pyrite, at least within experimental limitations of these two analytical techniques. The three-electrode system used for LSV studies had saturated calomel and platinum electrodes as the reference and auxiliary electrode, respectively. The studies included polarization experiments in aqueous solutions used in leaching and flotation processes.

RESULTS AND DISCUSSION

The rest potential (the open-circuit potential) of both types of pyrite electrodes change from a high of about +800 mV to a low of about +20 mV as the pH is changed from 1 to 13. A higher positive potential indicates noble behavior of the mineral at low (as well as neutral) pH's compared to other sulfide minerals, although at higher pH's pyrite tends to be more active. The voltammograms for both coal-pyrite and ore-pyrite in all of the aqueous inorganic systems studied have similar characteristics in terms of occurrences of current peaks at different applied potentials. This suggests that probably in aqueous inorganic solutions there is little difference in the behavior of ore-pyrite and coal-pyrite, and the small differences in our case may have resulted merely from the polycrystallinity of coal-pyrite and/or the presence of the coal phase in it.

In 0.1 N sulfuric acid solution, a cathodic peak at about -0.3 V and an anodic peak at about +0.9 V was observed in the voltammogram. An anodic attack at a low pH may occur by the following reaction:

$$FeS_2 + 8H_2O \rightarrow Fe^{+++} + 2SO_4^{=} + 16H^+ + 15e^-$$

and cathodic attack, which leads to the production of ferrous ions and hydrogen sulfide gas, by the reaction:

$$FeS_2 + 4H^+ + 2e^- \rightarrow Fe^{++} + 2H_2S$$

The evolution of hydrogen sulfide was observed in our experiments in a qualitative way (identified by the smell of the gas).

Sulfide minerals, including pyrite, can be leached at low pH's by the addition of Fe^{3+} ions, which provide a highly oxidizing medium. We carried out LSV studies in 0.1 M ferric chloride adjusted to pH 1.8 by the addition of hydrochloric acid, and the results are similar to those in the sulfuric acid studies, except that the peak currents are considerably higher. This indicates high reaction rates. Also, one cathodic and one anodic peak were observed at -0.4 V and +0.4 V, respectively -- peaks which were absent in the experiments with sulfuric acid. These peaks are probably due to the redox couple Fe^{2+}/Fe^{3+}.

For studies in alkaline medium, 1 N and 0.1 N sodium hydroxide solutions were used. The results were similar for both cases, except that the rest potentials of electrodes were higher and currents lower for the dilute solutions. The voltammogram for 0.1 N sodium hydroxide is shifted to more anodic potentials compared to the 1 N solution; that is, it required higher anodic over-potential to carry out the reactions at lower concentrations of NaOH. No distinctive peaks were observed in the voltammograms and the potential scan range which could be used was very short, mainly because of the active nature of pyrite at higher pH values. The reaction products of alkaline dissolution of pyrite have been suggested to be sulfate and ferric oxide. We were not able to confirm this through our experiments.

Comparison of voltammograms obtained for pyrite electrode in the presence and absence of potassium ethyl xanthate (a pyrite flotation collector) in 0.025 M borate solution indicates that dixanthogen is probably formed at the electrode surface.

As mentioned earlier, we have attempted to understand the leaching and flotation behavior of pyrite in various aqueous media from the point of view of studying the electrochemical reactions. Specifically, we compared the behavior of ore-pyrite and coal-pyrite under similar experimental conditions to ascertain whether the two types of pyrite involve different electrochemical reactions at the mineral-aqueous interface. Our studies have indicated that electrochemically speaking there is no significant difference in the leaching and flotation behavior of ore-pyrite and coal-pyrite. We feel that the difference in the flotation behavior observed by some researchers for coal-pyrite and ore-pyrite was probably due to the presence of some coal particles, attached to the coal-pyrite particles, in the sample used for their studies.

DETERMINATION OF THE PROPERTIES OF SOILS AND SOFT ROCKS BY IN-SITU MEASUREMENTS

J. K. Mitchell and W. C. B. Villet

INTRODUCTION

Accurate identification and characterization of subsurface conditions are essential for the economy and success of construction both in and on the earth. Reliable information on subsurface conditions in general, and specific geotechnical parameters in particular, is needed for the analysis of problems related to the utilization of underground space, subsidence, energy storage and extraction from the ground, and groundwater pollution owing to extraction or injection of fluids into the ground.

Traditionally, the required data have been obtained through sampling and testing of so-called "undisturbed" samples. There exist severe limitations to this approach, however, arising from such associated problems as sample disturbance, changes in sample properties due to unloading and exposure, and the difficulties attached to preventing or re-establishing in the laboratory the in situ state of stress as well as temperature, chemical, and biological environments. These limitations have become particularly evident as the volume of underground and offshore construction has increased. The need for reliable and improved techniques for site characterization and for the in situ determination of engineering properties of soil and soft rock has emerged as one of the most important geotechnical problems.

This research project, which was initiated in spring 1976, is concerned with the identification, development and implementation of new and promising approaches for site characterization and in situ measurement of soil and soft rock properties. A closely related objective is the evaluation of presently available techniques.

ACCOMPLISHMENTS IN FISCAL YEAR 1977

Emphasis in the research project thus far has been on the evaluation of existing techniques and on the development of a new approach based on the acoustic response of the ground during penetration at a constant rate.

Planned activities for 1977 were as follows:

1. Completion and publication of a state-of-the-art report on in situ measurement of soil properties

2. Further study and evaluation of the suitability and potential of remote and geophysical measurements to provide data from which quantitative measures of the mechanical properties of soil and rock may be deduced

3. Further study of acoustical measurements during quasi-static cone penetration tests as a basis for determining soil type and properties

Presently used in situ methods for the determination of soil and soft rock properties include:

1. Permeability tests by pump-in, pump-out and piezometer methods, employing both transient and steady state techniques

2. The Standard Penetration Test

3. Cone penetration tests of various types, including both static and dynamic methods

4. The Vane Shear Test

5. The Iowa borehole shear test

6. Pressuremeter tests

7. Plate bearing tests

8. Screw plate tests

9. Hydraulic fracturing tests

10. Down hole and cross hole seismic methods

A report has been completed and is in press. It presents a description of the various testing techniques, the evaluation theories or correlations for obtaining geotechnical parameters, an assessment of the suitability of each method for the determination of specific geotechnical parameters and their potential for future development. Extensive references are listed, and the report should serve as a definitive starting point for anyone interested in the subject.

Several less direct techniques for the in situ determination of site characteristics and soil properties are currently being studied. These predominantly involve applications of geophysical methods and include:

1. Seismic methods, including refraction, reflection, cross hole, and down hole techniques
2. Resistivity surveys including focused probes
3. Gravimetric methods
4. Magnetic methods
5. Nuclear methods - surface and subsurface
6. Radar methods
7. Spontaneous or self potential methods
8. Electro-magnetic methods
9. Thermometric methods
10. Remote sensing techniques such as GEOSAT

As a result of these studies a report is being drafted which will present the theory of each technique briefly, describe testing methods and evaluation theory, assess the current suitability of each technique for determining specific geotechnical parameters, and assess their potential for future development. It is intended that this report will serve as both a guide to what is currently feasible and as a stimulus to future research.

A penetrometer has been designed which measures the acoustic response of soils during quasi-static penetration tests. Permanent records are obtained using a tape recorder. The influence of soil properties and penetration procedure on frequency, amplitude, variability in both frequency and amplitude, and the distribution of acoustic energy over the frequency range of the generated signals are being studied.

Emphasis in the acoustic cone research is on:

1. Evaluation of the manner in which soil properties and testing procedures influence the acoustic signal generated during a quasi-static cone penetration test
2. Development of bases for the recognition of soil type, and the deduction of soil properties, from acoustic response spectra
3. Development of means for locating and evaluating very thin seams, which may have a large influence on ground stability, included between or within thicker zones.

It is believed that analysis of the sound generated during penetration may form the basis of an improved method for in situ soil "recognition," profile definition, and property characterization.

Support for a greatly expanded level of research on the acoustic response characteristics of soils during penetration has now been received from the National Science Foundation.

It may therefore be seen that the research project progressed very much as planned for 1977. The delay in publication of the state-of-the-art report on in situ measurement of soil properties has resulted from the time needed for extensive revision, editing, and typing of the manuscript. The report should, however, be available soon.

PLANNED ACTIVITIES FOR FISCAL YEAR 1978

It is understood that additional LBL support for this research will be limited and that the study will be phased out during fiscal year 1978. The main objective of the LBL-supported work will be completion and publication of the report on geophysical methods for site characterization and quantitative evaluation of soil properties.

HIGH PRECISION MASS SPECTROMETRY

M. C. Michel

INTRODUCTION

The interest in isotope measurements in geologic and cosmologic research has increased recently through the discovery of remarkable isotopic anomalies in several elements contained in a select group of carbonaceous chondrites, principally the one large meteorite, Allende. No definitive interpretation is possible as yet, but the new data will clearly put much-needed experimental restraints on theories of the origin of the solar system.

A less startling, but perhaps equally significant discovery has been that the earth's mantle shows strong evidence of preserving isotopic inhomogeneities for long periods of time, a fact that opens the possibility of a new technique for the study of mantle processes. Again, the data are difficult to interpret and workers in the field disagree on many details, but we are probably at the beginning of a new episode of research.

Each advance in isotope geochronology seems to increase the emphasis on achieving higher and higher precision in the experimental data, either to improve an existing technique (such as the Rb-Sr system) or to expedite the use of a new and potentially more useful system (such as the ^{147}Sm-^{143}Nd pair).

Last year we began a project to adapt our 5-ft radius isotope separator to high precision mass spectrometry through the simultaneous collection of several isotopes of the same element. This far from novel method has been standard for light element isotope ratios and would be even more advantageous for the heavier elements, most of which are not gaseous and therefore require ion sources that are inherently less stable in ion output. However, practical considerations have made it difficult to use this method on any but the largest mass spectrometers.

Preliminary work in fiscal year 1976 convinced us that it would be possible to measure isotopic ratios to a precision of one part in 10^5 using essentially commercially available amplifiers and digitizing equipment with relatively straightforward, custom designed auxiliary circuitry. Results in fiscal year 1977 have substantially verified that conviction although some work remains before an operating system can be tested. The remaining problems seem to be tractable.

ACTIVITIES IN FISCAL YEAR 1977

Since we originally intended to be able to apply the results of the mass spectrometric development to specific problems, we also included in our research plans the ability to do contamination-free chemical separations on geological samples, and isotopic dilution chemical analyses of selected elements such as rubidium.

The various activities planned and pursued during the year were as follows.

Ion Source Development

As explained in an earlier report, the ion source needed for the high precision work places rather stringent requirements on materials, design, and ease of fabrication (cost). Proceeding through about three basic design changes, a cavity-type, directly-heated thermal ion source was developed and tested which seems to meet the requirements as well as they can be defined at present. These are ease of loading, emission of ions from a well defined area, relatively constant ion output at constant temperature, high efficiency, and reasonable cost. Testing of the source shown in Figure 1 was done with strontium, but it should be adaptable to many other elements.

Contamination-Free Chemistry

In spite of considerably less than ideal laboratory facilities, a simple HCl eluant ion exchange technique was developed to separate rubidium and strontium from geologic samples, in forms and amounts suitable for isotopic ratio determinations and chemical analysis by isotopic dilution. Introduction of extraneous material of the same elements is well below the levels that would interfere with the measurements. For typical samples of strontium totaling a few micrograms, the strontium blanks are below 10^{-10}g.

Isotopic Dilution Analysis

Using another smaller mass spectrometer, a method of chemical analysis by isotopic dilution was developed and tested; the method allows analysis to a precision (but not necessarily accuracy) of about 0.2%. Testing was done with rubidium; other elements may deviate slightly in precision.

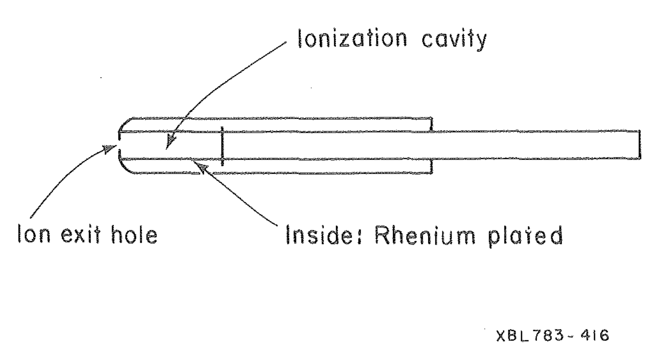

Figure 1. Cavity type thermal ion source. Material is tantalum except as noted.

Design of Four-Channel Data Readout for Isotope Separator

The greatest effort has gone into the design of a four-channel readout system that should have the ability to measure simultaneously four isotope beams to a precision of one part in 10^5 or better. Figure 2 shows a block diagram of this basically simple system. It is for the moment assumed that the input signals to each Faraday cup are properly representative of the relative abundance of each isotope (this may not be true for several experimental reasons which we will ignore at present).

Each Faraday cup signal is amplified by a separate amplifier which is essentially an impedance matching device, producing a low impedance voltage output proportional to the input current at very high impedance. Each channel could now be measured simultaneously by four voltmeters and the appropriate ratios calculated. For convenience the voltmeters are usually fast reading digital voltmeters which are easily arranged to read simultaneously.

It is obvious that several critical properties of this system determine the precision with which the isotopic ratios can be measured. These properties are: (1) the reproducibility, linearity, and time and temperature dependence of the amplifier gains and zero offsets (output with no input signal); (2) the linearity and short-term stability of the voltmeters; and (3) our ability to make all four amplifiers and voltmeters respond identically for reasonable times to arbitrary identical inputs.

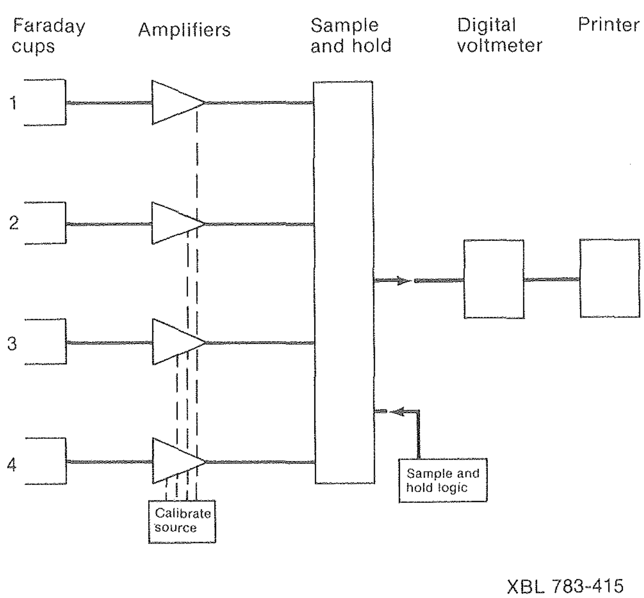

Figure 2. Block diagram of four-channel data system.

It became apparent that at least two commercially available small solid-state amplifiers would be suitable for this work. Extensive tests of their stability, time drift, and response to overload and noise sources showed that, given proper care, they have acceptable properties. They must also, as shown in the block diagram, be capable of calibration to identical gains by switching the same constant current source quickly among the four amplifiers and adjusting the gain to give identical outputs (note that knowledge of absolute signal sizes and gains is not necessary). This last requirement is clearly possible, and once calibrated, the stability is sufficient to make repeated measurements before recalibration is necessary. However, the best switching procedure has not yet been determined, it being very easy to generate a few microvolts of e.m.f. by various means common to switches and relays. For example, surface deformation of most metals can generate small signals which decay away slowly enough to present a serious problem in calibration of the amplifiers.

Assuming that the amplifiers are capable of giving an output accurately reflecting the Faraday cup inputs, we still must now measure each output voltage to a high relative precision. Accuracy is fortunately not critical, since no existing digital voltmeters can meet our requirements. However, all such instruments have much better short-term stability than accuracy, so if one is willing to intercalibrate them, it would be possible to make the desired measurements. To avoid this trouble and reduce the cost of the system, we developed a very simple capacitive sample-and-hold circuit which can collect data simultaneously from the four amplifier channels, preserve it and be sequentially read by a single digital voltmeter; this eliminates many problems. This circuit, controlled by a logic system, allows four capacitors to charge to the output of the four respective channel amplifiers. The level of voltage at any one time will be proportional to the average beam intensity input to the Faraday cup for that channel, and if all channels are also disconnected from their respective amplifiers at the same time, the voltage on each capacitor will likewise be proportional to the input beam. If the decay time-constant is long enough (several days) there will be time to measure all four capacitors sequentially with the same voltmeter and record the data on the output printer, or send it directly to a small computer for data processing. The results are a good approximation to a true simultaneous measurement of the four isotope beams. Note that the further integration of the beam currents by the sample-and-hold circuit in no way affects the precision of the isotope ratios; in fact it helps to eliminate the effect of beam fluctuations on the data.

Table 1 shows the noise levels or statistical uncertainties associated with the various parts of the system, as determined by a variety of test measurements on mock-ups of parts of the system. As is shown, a precision of 6 or 7 parts in 10^6 is possible. Because the test systems were less compact than the final design, and had many other disadvantages, we can expect a little improvement in the complete system, although there may be a

Table 1. Summary of noise and/or measurement uncertainties in a multiple channel readout system, based on individual component tests with simulated signals. Nominal signal = 1 V.

Source		Level, μV
1	Amplifer noise	2.5
2	Calibrate signal noise	2.5
3	Sum of 1 and 2	3.5
4	Collector noise/leakage	2.8
5	Sum of 3 and 4	4.5
6	Sample and hold error	< 1
7	Digital voltmeter error	< 1
8	Residual temperature coeff. error	< 1
9	Total	4.8
10	Error in ratio	6.8
11	Error after correction for fractionation	7.6

small absolute error that we cannot predict. Since recognized isotopic standards are already used to eliminate possible absolute biases between different laboratories, this will be disappointing but not a serious problem, even if it develops.

As soon as the requirements were firmly recognized, several commonly available digital voltmeters were tested in our laboratory with the same test systems used to determine the noise characteristics; one was selected for purchase.

PLANS FOR FY78

We plan to finish the four-channel system and test it extensively with strontium ion beams for which much data are available on the composition of various isotopic standards. In addition to demonstrating the success of our approach we can use this system to search for beam optical effects on the isotopic ratios to learn how sensitive the data are to minor malfunctions of the mass spectrometer, and therefore how reliable the entire system is over long periods of operation.

We plan to extend the work to the samarium-neodymium system at the first opportunity as well as to investigate the application of this system to lead and other element isotopic measurements.

Finally we will investigate the limitations on precision in the completed system to see what approach might be necessary to improve the precision to an even higher level. If a relatively non-fractionating ion source can be developed, an ultra high precision system would be of use in determining possible natural isotopic variations that are essentially linear with mass (as most physical processes will produce) as opposed to variations resulting from nuclear decay.

RADON IN SUBSURFACE WATERS AS AN EARTHQUAKE PREDICTOR, CENTRAL CALIFORNIA STUDIES

A. R. Smith and H. A. Wollenberg

We have investigated whether variations in the Rn-222 content of subsurface water can be a useful earthquake prediction parameter in California. Using NaI(Tl) crystal γ-ray spectrometry, high sensitivity high-precision measurement techniques and instrumentation have been developed for both laboratory analysis of discrete samples and continuous monitoring at field installations. Precision and reproducibility were regular within 1-3% in the laboratory; precision of 1% was achieved from counting periods as short as 10 minutes at field stations.

These techniques were applied to determine the validity of the radon method. A discrete sampling program was conducted in the Oroville, California area for 20 months during the aftershock sequence that followed the August 1975 earthquake of Richter magnitude ~6. Through use of a local volunteer organization, we maintained a daily sampling schedule at several wells throughout the study period, and obtained approximately 3000 samples. Since July 1976, a continuous monitoring station has been in operation at San Juan Bautista in Central California along an active segment of the San Andreas Fault.

The program continued in 1977 at a much reduced level, as dictated by severe funding restrictions. Thus, sampling of wells during the aftershock sequence of the Oroville earthquake was terminated in April 1977. The field program consisted of a monitoring station, located on the San Andreas Fault near San Juan Bautista, operated through assistance from the U.S. Geological Survey National Center for Earthquake Research. The Oroville data show apparent correlation between some radon changes and subsequent seismic activity, but does not yet represent conclusive evidence for validity of the method. The San Juan Bautista data suggest there is correlation between some periodic radon changes and earth tides. In both cases, data interpretation has been complicated by the severe drought conditions.

The major effort of 1977 was to prepare a comprehensive summary report for the study period 1975-1977.[1] Computer codes were written to assist in analysis of data to search for correlations between radon level changes and nearby seismic activity, as at Oroville. These results were reported at the American Geophysical Union 1977 Fall Meeting at San Francisco, December 1977.

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STRESS FLOW BEHAVIOR OF FRACTURED ROCK SYSTEMS

R. L. Taylor, P. A. Witherspoon, H. M. Hilber, and J. van Greunen

INTRODUCTION

The mechanical behavior of fractured rock masses is sensitive to the effects of water flowing through the discontinuities of the system. There is evidence of a connection between seismic activity and the increase in pore pressure within the earth's crust. Low to medium magnitude earthquakes have been reported in connection with the filling of what are called "seismic dams."[1-4] The possibility that a change in fluid pressure in a fractured system might cause the release of tectonic stresses has been indicated by events at Rocky Mountain Arsenal Well near Denver, Colorado.[5-7] More recently, evidence has been gained at the Rangely, Colorado oil field that fluid injection has triggered small earthquakes along a fault.[8-10] Thus, the concept is now developing that if earthquakes can be caused by injecting fluids into the subsurface, then perhaps the appropriate control of fluid pressures in the fracture system of a fault can lead to a method of earthquake control.[11]

The feasibility of such a concept must be carefully investigated using a combination of analytical-numerical and experimental approaches before it can be developed into a practical model. As a first step, the concept should be tested by numerically and experimentally analyzing the behavior of simple laboratory models. Hence, numerical methods have to be developed such that a broad class of laboratory tests and field situations can be simulated.

Recently several attempts at developing appropriate computational models have been reported.[12-17] In previous studies a two-dimensional finite element formulation has been developed to simulate quasi-static processes in systems of deformable fractured rock.[13-15] The dynamic nature of slip mechanisms limits the applicability of the quasi-static model to study of pre-failure conditions. Dietrich developed a dynamic finite element model for a single fault that undergoes slip under the influence of tectonic and predetermined fluid stresses.[18] This model was not designed to incorporate the interactive processes between the fluid pressure, the fracture deformations, and the stresses in the rock.

Since the available computational models seemed to be unnecessarily restricted, an effort was made in the present study to develop an improved numerical procedure for simulating transient interactive processes in systems of fractured rock.

The goal of the 1-year study was to continue the development of a finite element method computer program to model the dynamic response of two-dimensional systems of fractured rock subjected to injection and/or withdrawal of fluid from the fractures. The original program development was initiated under NSF contract number GK-42776 by the first two authors at the University of California, Berkeley, and is reported in Ref. 19. A second objective was to perform analyses on some typical problems to illustrate the kind of results which can be obtained using the program.

ACTIVITIES

The activities described in this report commenced on 1 September 1976 and ended on 31 August 1977. A summary of the activities is given below.

The equations governing the behavior of fractured rock systems subjected to fluid injection and/or withdrawal are given by the equations of motion for the fractured rock system and the continuity equation for the fluid flow. After discretization using standard finite element methods the resulting nonlinear ordinary differential equations are

$$\underline{M}_S \, \ddot{\underline{u}} + \underline{K}_S \, \underline{u} + \underline{K}_J(\underline{u}) = \underline{R} + \underline{B} \, \underline{P} \qquad (1)$$

for the equation of motion and

$$\underline{B}^T \, \dot{\underline{u}} + \underline{K}_F(\underline{u}) \, \underline{P} = \underline{Q} \qquad (2)$$

for the continuity equation.[19,20] In the above equations $\underline{M}$ is the mass matrix; $\underline{K}_S$ is the rock stiffness matrix; $\underline{K}_J$ is the internal force vector in the joints; $\underline{u}$ is the nodal displacement vector; $\underline{P}$ is the nodal pressures due to fluid in joints (fractures); $\underline{R}$ is the external nodal forces on the rock system; $\underline{B}$ is the transformation matrix for pressures and velocities; $\underline{K}_F$ is the flow matrix; $\underline{Q}$ is the vector of nodal flows added or removed; $(\ )^T$ indicates the matrix transpose, and nonlinearities are indicated by an argument on the appropriate term. Finally, the subscripts S,J, and F refer to solid rock, jointed rock, and fluid, respectively. The coupling between fluid pressure and displacements is clearly seen in the above equations. We solve the above non-linear equations as follows. The time is discretized and derivatives are replaced by the one-step Newmark formulas.[21] The nodal displacement and fluid pressure at each discrete time are chosen as the primary dependent variables, resulting in a coupled set of non-linear algebraic equations to be solved at each time step. Due to the strong coupling we solve these by first getting the fluid pressures based on the current values of the nodal displacements. Using these pressures we then solve for new estimates to the nodal displacements. The process is then repeated until convergence is achieved, usually in very few cycles through the equations. At each step, stick-slip conditions are checked for each joint; for joints that have shear greater than the dynamic frictional resistance, slip is allowed. The finite element program developed for this analysis is called FAULT and can handle general two-dimensional problems.

One of the difficulties encountered in solving problems was the situations in which joints with extremely small apertures existed. In this case the opening and closing of the joint caused very rapid changes in pressure [this is the $\underline{B}^T \dot{\underline{u}}$ term in (2)] which are unlikely to occur in real situations. In this case a surge (or change in elevation of the fluid surface) will occur with rather small change in pressures. For this case we merely ignore the $\underline{B}^T \dot{\underline{u}}$ term in (2). In any future work some improvement is necessary, a surge term should be considered. The surge term is a three-dimensional effect and it may be necessary to have a fully three-dimensional model to consider this case. On the other hand, it may be possible to develop equations for the joints which are analogues to the shallow water equations and still retain the two-dimensional modeling for the jointed rock system.

To facilitate use of the program, a graphics package was developed and incorporated into FAULT for use on the LBL system. In addition to mesh plots the package can produce time plots for specified nodal displacements, velocities, accelerations and stresses, as well as fluid pressure and energy quantities.

In Figure 1 we show the mesh of a typical problem considered during the project together with the injection/withdrawal pattern along the principal joint. In Figure 2, the stick-slip characteristics are shown for two static/dynamic friction ratios α. Slip initiates at the static value and continues at the dynamic value until stick again occurs. Figure 3 shows typical displacement velocity and acceleration traces at a node. The resemblance to typical earthquake motions is noted in these traces.

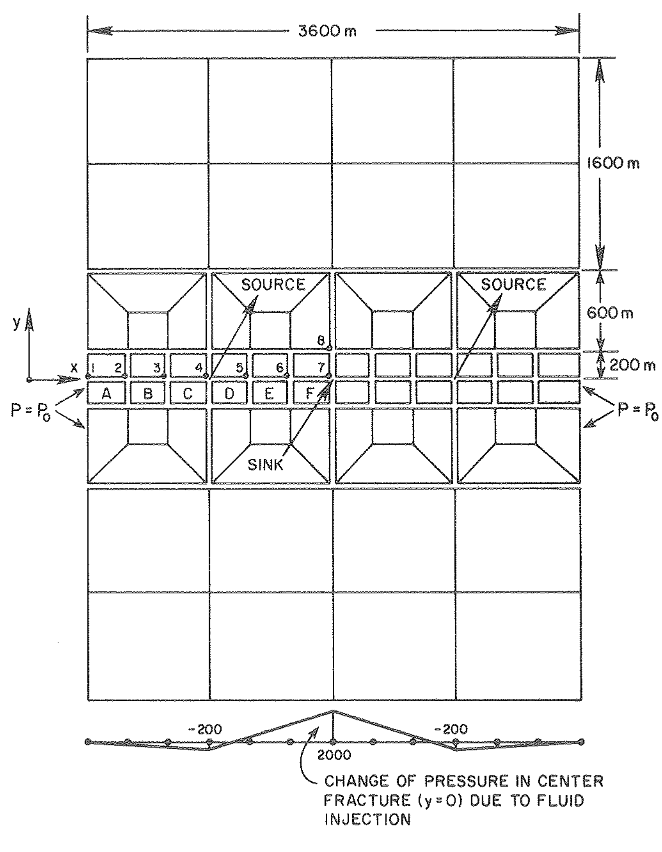


Figure 1. Finite element mesh of a tectonically stressed straight fault system.

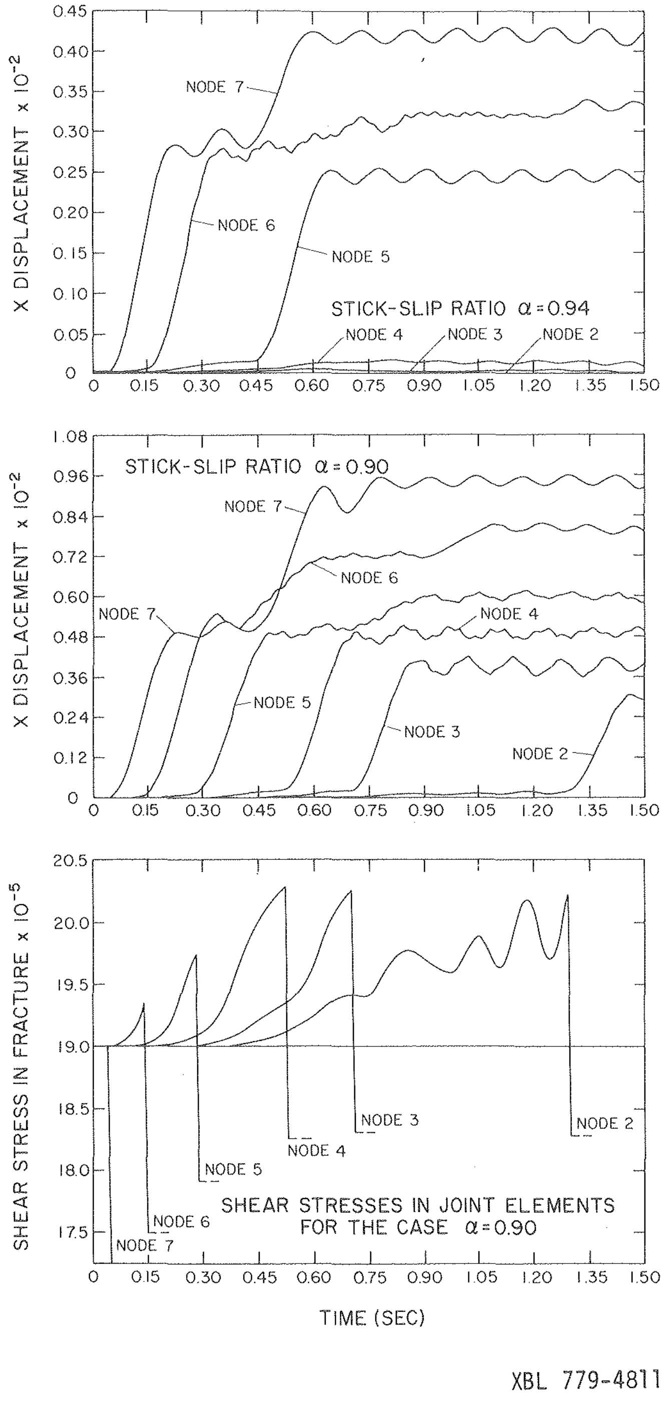
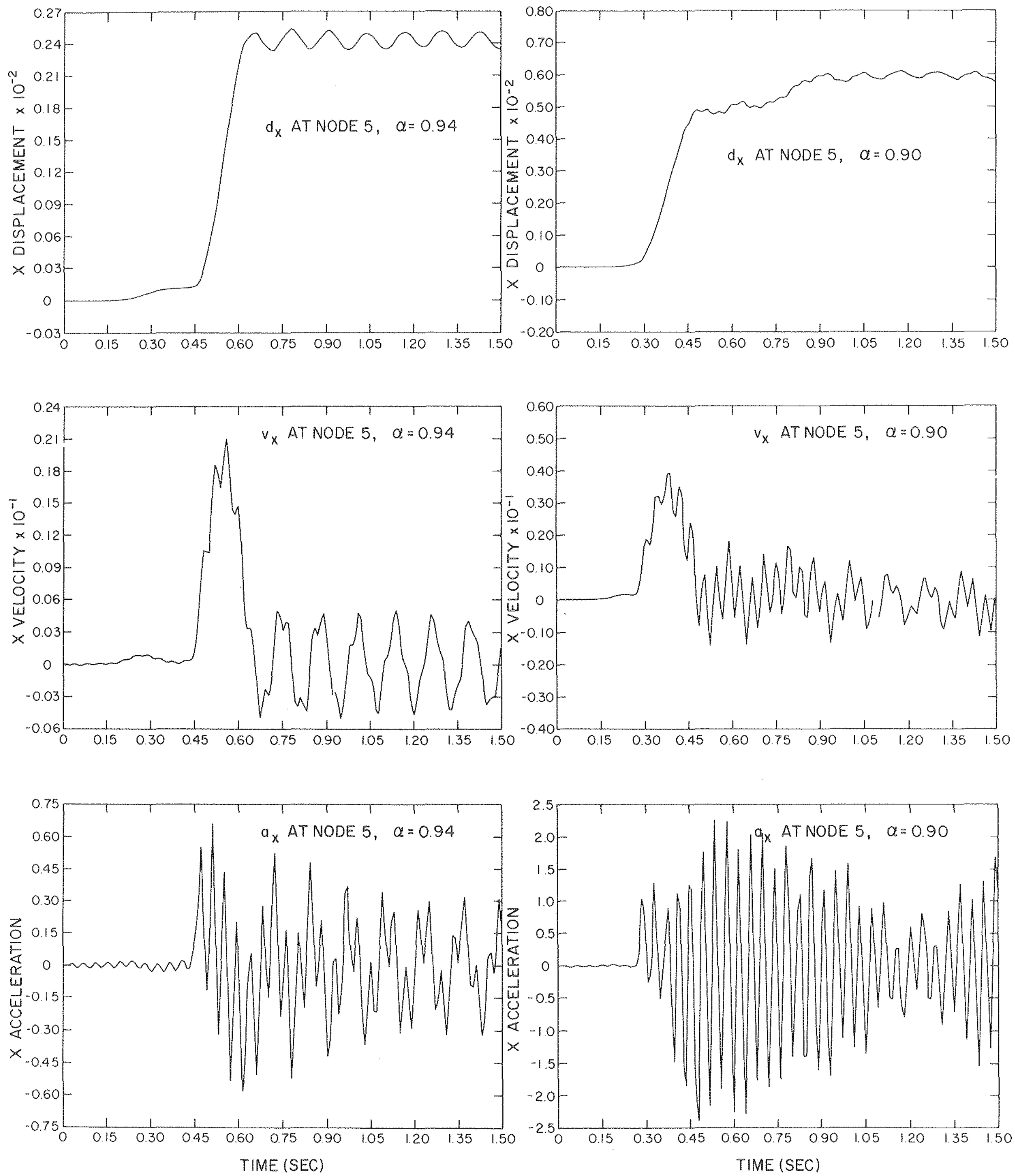


Figure 2. Displacement histories and shear stress drop at points along central feature.



XBL 779-4812

Figure 3. Displacement velocity and acceleration of node 5 in direction parallel to fault.

In conclusion, we have developed and demonstrated a numerical analysis tool to simulate the dynamic response of two-dimensional fractured rock systems subjected to fluid injection or withdrawal. In addition to demonstrating a possible mechanism for earthquakes, the program can be used to study possible methods for control of earthquakes. Finally the program can be used to generate earthquake records for use in other analysis methods.

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3. GEOTHERMAL ENERGY DEVELOPMENT

The present Earth Sciences Division program in geothermal energy development began in 1973 in response to the national goal of developing alternate energy sources. To stimulate industrial development of geothermal resources for electric power generation, the LBL program initially consisted of: an assessment of geothermal sites in northern Nevada; development of a binary-fluid power plant for high-temperature, low-salinity brines; and various geochemical and geophysical studies related to the thermodynamics and chemistry of brines and the properties of reservoir rocks. An additional support project, the National Geothermal Information Resource (GRID), commenced with the responsibilities for compiling data on geothermal energy and for operating a computer data base.

Many of these geothermal programs continue and many more have begun, including those discussed in Section 2 of this report. In this section, there are five major project categories: geochemical engineering, reservoir engineering, subsidence research, utilization and conversion technology, and exploration technology.

The geochemical engineering projects are concerned primarily with geothermal fluids, the chemistry and thermodynamics of brines, and scaling problems.

Reservoir engineering studies have three components: the development and testing of new methods of numerical modeling for reservoir evaluation; the evaluation of particular geothermal reservoirs; and development and management of the Geothermal Reservoir Engineering Management Plan (GREMP).

The subsidence research program plan is managed by LBL, which is also modeling subsidence effects due to fluid withdrawal.

The utilization and conversion technology projects include experimental studies and computer simulations of processes for power conversion. LBL has continued to manage field operations for the DOE Geothermal Component Test Facility (GCTF) at East Mesa, Imperial Valley, California. The Laboratory is also formatting and analyzing production data for DGE and the San Diego Gas and Electric Company from the Geothermal Loop Experimental Facility (GLEF) at Niland in the Imperial Valley. It is also assisting DGE in coordinating their direct-contact heat-exchanger program.

Exploration technology projects are concerned with the development and improvement of geophysical and geochemical exploration methods. For several years, technique evaluation (principally in northern Nevada) and geophysical data interpretation have been major activities at LBL. New projects include development of a controlled-source electromagnetic prospecting system and support for a DOE resource evaluation at Mt. Hood, Oregon. Exploration technology developed in the past by LBL is being applied to reservoir evaluation studies at the Cerro Prieto Geothermal Field, Baja California.

NATIONAL GEOTHERMAL INFORMATION RESOURCE

S. L. Phillips and S. R. Schwartz

INTRODUCTION

The National Geothermal Information Resource (GRID) is sponsored by the U.S. Department of Energy (DOE) to develop and maintain a central geothermal data center, making information accessible to scientists and the industrial community. The program includes site-dependent and site-independent data related to geothermal energy explorations, electrical and direct utilization, environmental questions, and aqueous electrolyte properties. The program was initiated in fiscal year 1974 with funding provided from the U.S. ERDA Division of Physical Research. Currently, the program is supported by DOE's Division of Basic Energy Sciences, the Division of Geothermal Energy and the Office of Environmental Information Systems, Division of Biomedical and Environmental Research.

The GRID program uses the Berkeley Data Base Management System to create and maintain, and disseminate bibliographic and numerical data. Data are readily retrieved from the GRID database by specifying one parameter, such as the geothermal site, or a combination of parameters, such as the geothermal site, the date, and the designated data measurement. Data output is available in the form of bibliographic compilations, numerical tables or graphic displays on paper, film, or magnetic tape. In addition to maintaining a current geothermal data base, the program staff are responsible for literature reviews and critical evaluations of the status of data.

The project also cooperates in the exchange of information and data with other organizations on a worldwide basis. There are currently three

U.S. data centers working to implement the collection and exchange of information on geothermal energy research and production: the DOE Technical Information Center (TIC), Oak Ridge, Tennessee; the GEOTHERM project of the U.S. Geological Survey in Menlo Park, California; and the GRID project. The data systems of TIC, GEOTHERM and GRID are coordinated for data collection and dissemination, with GRID serving as a clearinghouse, having access to files from all geothermal databases including both numerical and bibliographic data. GRID cooperates with DOE/TIC for bibliographic information and with the U.S. Geological Survey for certain site-dependent numerical data. The GRID program also cooperates with relevant data programs, such as the National Standard Reference Data System and others, for collection of numerical data.

The GRID program's standards for interchange of bibliographic data are patterned after the International Atomic Energy Agency's International Nuclear Information System (INIS). Utilization of the INIS format ensures that GRID's data will be compatible with other INIS-styled data centers, thereby promoting the active interchange of data with other groups.

BIBLIOGRAPHIC FILES

The GRID geothermal bibliographic file is on line for computer searches and contains the following new and updated subsets:

Environmental/Hydrogen Sulfide

Geothermal vapor and hot water fluids contain a fraction of noncondensible gases composed mainly of carbon dioxide with lesser concentrations of hydrogen sulfide and other gases such as methane, ammonia, nitrogen, hydrogen and ethane. The interest in H_2S aspects of geothermal energy is mainly related to the problem of corrosion of materials and environmental effects. Although this file highlights the geothermal aspects of hydrogen sulfide, substantial references from other sources of H_2S are included, for example: petroleum refining, smelting of sulfide ores, the manufacture of Kraft pulp, and offal rendering plants. Currently, the topics referenced in the hydrogen sulfide file include the following: sources of H_2S, monitoring methods, emission control, environmental effects, health effects, pathways in the air and water environments. The hydrogen sulfide file is the result of an initial screening of the worldwide literature and new citations will be appended periodically.

Environmental/Land Subsidence

The land subsidence file is on line and is available for restricted searches. Topics in the file iclude subsidence resulting from mining operations and petroleum production, and subsidence associated with geothermal fluids withdrawal.

Physical Chemistry/Aqueous Electrolytes

An updated version of the aqueous electrolytes file is available for searches and contains references on basic energy data for aqueous electrolytes (such as enthalpy, vapor pressure) to elevated temperatures and pressures.

Exploration/Geothermal Site Data

An updated version of the geothermal site file is available for searches and includes bibliographic information on the following topics: hydrology, location, drilling, geology, land-use factors, and geochemical and geophysical measurements.

Utilization/Brine Treatment

The brine treatment file is available for computer searches on the following areas: geothermal fluids, piping and wells for scaling and corrosion, and treatment data for controlling scaling.

NUMERICAL FILES

The GRID geothermal numerical data files are also available for searches and contain the following new and updated subsets:

Noncondensible Gases

A numerical file containing data on noncondensible gases (such as H_2S, CO_2) at geothermal areas is in preparation by the GRID project staff. The file is designed to include descriptive information such as geothermal well location, sampling method and sampling date, and technical information such as well-head pressure and gas output. A sample subset on the Wairakei geothermal field is on line for searches by interested users. In the future the file will include all domestic geothermal sites and additional foreign sites, e.g., the Larderello field in Italy and the Cerro Prieto field in Mexico.

Geothermal Power Plant

This numerical file covers the following typical site dependent data for geothermal power production facilities: production well characteristics, injection well characteristics, and data on flash drums, scrubbers, stages, heat exchangers, and generators.

Fluids Chemistry

The fluids chemistry numerical file developed with the LBL Geoscience Engineering program is available for searches. The file contains data on the chemical components of geothermal hot waters.

Sodium Chloride Aqueous Solutions

The aqueous NaCl file is available for searches and contains numerical data on density and viscosity to elevated temperatures and pressures.

INFORMATION EXCHANGE WITH OTHER DATA CENTERS

Domestic

Involvement in information exchange currently includes cooperation with TIC and GEOTHERM.

Future cooperative efforts are expected to include those with CODATA, COGEODATA, and the National Standards Reference Data System.

International

When ERDA was formed in 1975 it inherited several international agreements from the AEC. Among these were bilateral and multilateral agreements on the exchange of information and scientists in various technical areas such as fossil, fusion, solar, and geothermal energy. As a result of The NATO Committee on the Challenges of Modern Society (CCMS) meeting held in New Zealand in 1974, the U.S. and Italy agreed on the exchange and collection of information regarding the development and exploration of geothermal energy resources.

Under the agreement, GRID has provided the Italian contact, Consiglio Nazionale delle Ricerche (CNR), with the following material:

1. computer tape containing the geothermal bibliographic file 1976 (TID-3354 R1) from TIC, Oak Ridge;
2. computer tape and printout containing the data file on geothermal fluids from the LBL geochemical engineering program; and
3. computer data containing geothermal data from the GRID group.

The United States, via GRID, received a computer tape from Italy containing geothermal references from their data center.

Under the terms of the agreement, DOE is responsible for coordinating the collection of geothermal data from Central and South America. GRID has been identifying individuals who will function as permanent contacts for development of information exchange programs.

FUTURE WORK

In February 1978, the thermal conductivity data for aqueous sodium chloride solutions will be compiled and disseminated. Enthalpy data on sodium chloride solutions is expected to be critically evaluated, a correlation expression developed, and the results of the work disseminated in the first half of 1978. Data on other basic properties (such as electrical conductivity and heat capacity) will be compiled in the last half of 1978.

In 1978 we also expect to add to and edit the magma file and seek funding for the drill-hole survey file. A major effort will be compiling critically evaluated site-dependent data covering the information categories listed above.

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GEOCHEMICAL ENGINEERING

The purpose of the Geochemical Engineering project is to furnish interpretive support for investigations into the control of chemical problems in geothermal power conversion. This project was designed to meet certain urgent objectives of the DOE/DGE program in Geochemical Engineering and immediate industrial needs.

Geothermal fluids contain silica, carbonates, chlorides, carbon dioxide, hydrogen sulfide, and other gases and salts. The major problems encountered during the operation of a geothermal power plan are silica scaling, carbonate scaling, air pollution and corrosion problems associated with hydrogen sulfide (H_2S) and its oxidation products, and removal and rejection of the noncondensible gases, chiefly carbon dioxide (CO_2).

This project was started in fiscal year 1976. During fiscal year 1977 it consisted of three tasks:

1. characterization of the chemical composition of geothermal fluids;

2. management support for the ERDA/DGE program in scaling and corrosion control in geothermal systems; and

3. development of a qualitative model for the mechanisms of silica scaling from geothermal systems.

Tasks (1) and (2) were completed by the end of fiscal year 1977. Task (3) will continue to be directed, during fiscal year 1978, toward the development and demonstration of engineering equations, modeling silica scaling mechanisms in geothermal fluids.

In addition, two new tasks will be added: (4) analysis of possible chemical problems associated with the thermal decomposition of binary heat exchange fluids; and (5) technical consultation and management support for R. Feber in the area of coordinating the ERDA/DGE brine chemistry modeling projects among themselves and with other ERDA-supported, industrial and international programs.

A COMPILATION OF DATA ON FLUIDS FROM GEOTHERMAL RESOURCES IN THE UNITED STATES *

S. R. Cosner and J. A. Apps

BACKGROUND

The commercial development of geothermal energy for power and heating is receiving serious attention in the United States. Many resources are being investigated intensively, and the design and testing of geothermal systems and components is under way, both in government national laboratories and in the private sector.

Geothermal energy can be extracted from resources containing native steam, hot water, geopressured water, hot dry rock, and magma. However, the most important resources, in terms of immediate development potential, are those containing hot water. Such resources are generally known as "liquid dominated" in contrast to "vapor dominated" or native steam sources.

The liquid-dominated resources vary substantially in size, temperature, and fluid composition. When such resources are exploited, the variation in fluid composition leads to many technical problems, including scaling, sludge formation, corrosion and erosion in surface facilities, the disposal of noncondensible gases, the treatment of toxic gases, volatiles and precipitates, and the disposal of spent fluids. Geothermal fluids also have thermodynamic and transport properties that differ from pure water, which must be taken into account during geothermal power plant design. A knowledge of geothermal fluid characteristics is therefore important in anticipating such problems.

The purpose of this compilation is to provide information on the chemistry of geothermal fluids to scientists and engineers who are responsible for the development of geothermal energy from hot water resources. The compilation provides a comprehensive tabulation of available data on geothermal fluids from the most important geothermal resources in the United States.

The work was funded by the Division of Geothermal Energy of the Department of Energy.

SCOPE OF THE COMPILATION

Resources Selected

The resources selected for the compilation were determined primarily from White and Williams.[1] Liquid-dominated resources, with a heat capacity exceeding 1×10^{18} calories and temperatures greater than 90°C, were candidates for inclusion in the data compilation. However, the resource at Yellowstone Park was omitted because exploitation of the geothermal resources in national parks is prohibited. (Thirty-four candidates were identified.[1]) In addition, resources at Cerro Prieto, Mexico, and Puna, Hawaii, were included. The former was added because of its relevance to other geothermal resources in the Imperial Valley, California, and the latter, because of significant drilling results obtained in 1977.

The resources chosen were those most likely to be exploited for geothermal energy during the next 10 years. Particular importance was attached to their potential for electric power generation.

Only information on the chemical composition of fluids from wells was compiled. Hot-spring analyses were not collected because such analyses are not considered to be representative of geothermal fluids found at depth within a geothermal reservoir. The U.S. Geological Survey is conducting a program to collect data on hot springs in the United States.[2]

Data from 17 resources were obtained by searching the literature, and by collecting data from companies working in the geothermal energy field. The literature search includes references dating back to 1929. Much data held by the private sector remains confidential because of the need to protect corporate investments in a promising geothermal area. For this reason much information

* Extracted from LBL Report No. 5936

is lacking from wells drilled recently, specifically Valles Caldera, New Mexico (Baca location No. 1, KGRA); Brawley KGRA, Imperial County, California; and Roosevelt Hot Springs KGRA, Beaver County, Utah.

Information Compiled

A complete listing of information which could be compiled for each sample is shown in Table 1. Not all information could be found for each analysis. All information is recorded as found in the source document. For example, no attempt was made to standardize units of measurement for the concentrations of components in solution.

Caution must be exercised in using the data in this compilation. The data come from a large variety of sources and are of variable quality. Users should be cognizant of the type of sample, the way in which it was obtained, the completeness of the analysis, the analytical methods, and the units of measurement in which the results are reported. Some samples may have been analyzed long after collection, leading to interim oxidation, precipitation, or evaporation of some of the constituents.

It should be recognized that geothermal fluids are rarely, if ever, uniform in composition. The analysis given for a particular geothermal well may not be representative of the resource as a whole. It may be little more than a reflection of an unspecified mixture of fluids of differing compositions from different horizons within a well. The composition of geothermal fluids can also change with time. Compositional fluctuations may occur in a flowing well during time periods as short as one hour.

COMPUTER PROCESSING

Storage of and Access to the Data

The compilation of geothermal fluid data has been processed and stored at Lawrence Berkeley Laboratory, using the Berkeley Database Management

Table 1. Data elements of the geothermal fluid data compilation.

PRELIMINARY INFORMATION
Code name (well name and a unique letter for each record of data from that well)
Well Name
KGRA or geothermal field
Location (township, range, section, quarters or other delineation)
County
State
Country
Well owner
Lessee of well
Drilling company
Dates drilled.

WELL INFORMATION
Well depth (in meters)
Temperatures (°C)
Depth or location of temperature reading
Shut-in pressure
Flow information (flow rates and pressures)
Well casing perforation interval
Lithology of production zone

SAMPLING INFORMATION
Type of sample (water, steam condensate, noncondensable gases)
Date sample taken
Sample number, analyzing laboratory
Location sample taken
Sampling method
Condition of sample when taken (temperature, pressure, whether fluid lost due to steam flashing)
Condition of well when sample taken (flow time before sampling, flow rate, etc.)

PHYSICAL DATA
pH, pH range if given, temperature of reading
Eh, temperature of reading
Specific gravity, temperature of reading
Viscosity of fluid
Total dissolved solids, whether sum of analysis or residue on evaporation
Total alkalinity
Other data

CHEMICAL ANALYSES DATA
Methods of analysis
Error limits
Units
Constituent name, concentration, comment
Comment, if needed, on table of analyses

BIBLIOGRAPHIC DATA
Sources of data in record (Entry corresponds to the principal author's last name and year article was published)

OTHER NOTES
Other important information

System (BDMS). This system is a generalized information retrieval system offering a broad range of capabilities for creating, maintaining, and accessing computer databases. BDMS consists of an easy-to-use database definition language, an editor that stores, modifies and retrieves data, and a system that searches the database for indices specified by the user.[3]

The compiled geothermal fluid data are stored in the database as records. Within each record, data are stored under data elements. These data elements are defined by the database user. Over 50 elements were defined for use in the geothermal fluid data compilation as shown in Table 1. Few records contain all of the data elements since the information compiled was usually incomplete.

Each record is unique for a specific sample analysis from one well (Fig. 1), unless there is more than one analysis for a well, in which case there are multiple records. An attempt was made to place the most reliable analysis in the first record.

Because the compilation is stored on the LBL computer system, users can gain access to it through a computer terminal. With special arrangements a user may connect to the LBL computer via a telephone line and a remote terminal, and inspect the data on this terminal. This connection also allows the user to search selectively for specific subjects, and to print just those records of interest.

A more complicated operation using compilation through computer access involves the manipulation of the data in user-written programs. This could be done, for example, using the data as input for a program modeling thermodynamic equilibria of a geothermal system. Programs could also be written to make statistical comparisons of various parameters stored in the compilation.

Bibliography

The bibliography for the geothermal fluid data compilation shows all the sources from which data were collected. The bibliography, like the data compilation, was input to the BDMS computer to facilitate editing and retrieval on specific subjects. The format used is the same as that used by the National Geothermal Information Resource group (GRID) at LBL.[2,4] The descriptors for each reference are key words, taken from a standard thesaurus,[5] which describe the subject matter discussed in the report of article. These key words facilitate computer searches for specific subjects.

The name and number in the upper right section of each bibliograhic listing is made up of the principal author's last name and the year the article was published. This entry corresponds to that listed as the source of data at the end of each record in the fluid data compilation.

The bibliography contains listings of some reports and articles that were not used as sources in the compilation. They were scanned for data, however, and are included in the bibliography since they may be useful to investigators.

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RECORD 167
CODE NAME=NOWLIN 1
SAMPLE TYPE=WATER

WELL NOWLIN 1
HEBER KGRA
LOCATION--T16S, R14E, SEC. 33, 2873FT S, 3554FT E, FROM NW
CORNER, IMPERIAL COUNTRY, CA., USA

WELL INFORMATION
OWNER--CHEVRON OIL CO.
DATE DRILLED--10 MAR 72 - 13 NOV 72

WELL DATA
COMMENT--GEOTHERMAL WATERS AT HEBER ARE PRODUCED FROM A
DEPTH OF 600 TO 1900M.

PHYSICAL DATA
PH=7.10
TOTAL DISSOLVED SOLIDS=14100.00 PPM

BRINE DATA
UNITS--PPM

CONSTITUENT	CONCENTRATION	COMMENT
SIO2	120	
NA	3600	
K	360	
LI	6.6	
CA	880	
MG	2.4	
CL	9000	
F	1.6	
SO4	100	
HCO3	20	
CO3	4	
AL	.04	
B	4.8	
CU	.2	
FE	.9	
PB	.1	
ZB	.68	
CO2	------	TRACE
H2S	------	TRACE

THERE ARE ONLY TRACES OF CO2, H2S AND OTHER NONCONDENSIBLE
GASES IN THE HEBER GEOTHERMAL FLUIDS.

BIBLIOGRAPHIC DATA
SOURCE--
EPRI 76A
WITHAM 76

Figure 1. Sample record from the Berkeley Database Management System.

DEFINITION OF ENGINEERING DEVELOPMENT AND RESEARCH PROBLEMS RELATING TO THE USE OF GEOTHERMAL FLUIDS FOR ELECTRIC POWER GENERATION AND NONELECTRIC HEATING

J. A. Apps

INTRODUCTION

The use of geothermal fluids for electric power generation and nonelectric purposes causes problems not normally encountered when pure water is used for similar purposes. Before geothermal energy can become an important source of electric power or thermal energy in the United States, these problems must be identified and solved.

A list of research and development projects aimed at solving those problems arising from the use of geothermal fluids from known sources in the United States has been compiled in LBL-7025. Problem areas covered are: the impact of chemical, thermodynamic, and transport properties of geothermal fluids on engineering design; scaling and sludge formation; gases, volatile brine constituents, and condensate chemistry; and environmental

* Extracted from LBL Report No. 7025

considerations. Other areas, such as the corrosion and erosion of materials and the development of new materials for plant and well construction, are not discussed.

The research projects identified are general in nature and are not site-specific. The development of geothermal resources in the United States is still at a preliminary stage, and available information about the resources is insufficient to predict site-specific problems with certainty.

OBJECTIVES

The report forms the basis of a national plan to quicken the exploitation of domestic sources of geothermal energy. The goals of the program are to: define potential problems and reduce risk; determine the best design for any given field; reduce capital costs for plant and ancillary equipment and extend plant life; improve plant reliability and reduce routine maintenance; and reduce environmental problems.

Secondary goals are to: use waste heat effectively; and to generate revenue from geothermal fluid byproducts (such as salt, potash, and nonferrous metals) and from the production of fresh water.

The report may be used to develop and implement a national plan. However, other strategies may be adopted, which would lead to an equally effective outcome.

ORGANIZATION OF THE REPORT

The task of identifying research and development projects pertinent to the problems specified in the Introduction requires consideration of many factors. (A flow chart is presented in Figure 1 showing the impact of each factor in a logical sequence and the organization of LBL 7025). The task is accomplished in three stages.

Stage 1: Characterization of Geothermal Fluids

1. Identification of geothermal resource types and classification of geothermal fluids.

2. Identification of geothermal fields most likely to be exploited in the near term, and the characterization of geothermal fluids from these fields.

Stage 2: Program definition

1. Identification of engineering problems resulting from the use of geothermal fluids in each fluid class.

2. Categorization of research and development projects relating to the four problem areas considering the energy conversion systems most likely to be used for each class of geothermal fluid.

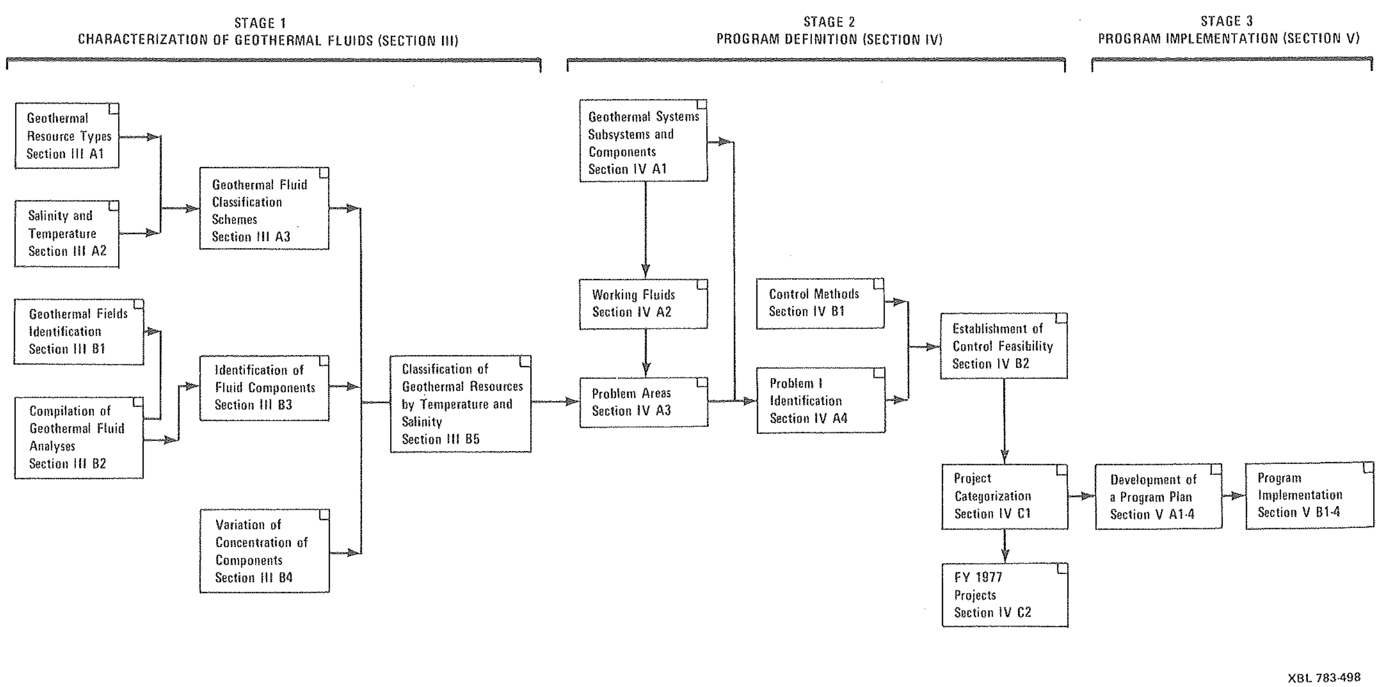

Figure 1. Flow chart showing the organization of LBL Report 7025.

Stage 3: Program Implementation

1. Development of a program plan.

2. Implementation of the program.

The various factors included in each Stage are indicated by a series of matrix charts, the output of one chart serving partly as the input for the next. The first part of Stage 1 involves the classification of geothermal fluids on the basis of geothermal resource types, salinity, and temperature. In the absence of more definitive studies, a professional assessment had to be made as to which geothermal resource types would be most likely to be exploited in the near term (~10 years). The next part, the identification of geothermal sites, is based primarily on a selection from the listing given by White and Williams.[1] Sites from the listing are restricted to a minimum size of 10^{18} calories and a minimum temperature of 90°C. Other criteria, limiting the choice of sites still further, such as distance from population centers, chemistry, and the impact of temperature on well costs, are discussed but not investigated because of the need for extensive study of each site.

The remaining parts, involving the characterization and classification of geothermal fluid compositions from the sites selected previously, are also incomplete. However, preliminary estimates of the distribution of critical components have been made. A separate project has been completed in which geothermal fluid data from the selected sites have been compiled in a computer file. A report tabulating all data compiled will be released in 1978.[2] Further evaluation of these data is continuing, and an LBL report on the characterization of geothermal fuids was released in 1977. Sites for which geothermal fluid data are available are classified according to temperature and salinity. This classification, when combined with a knowledge of the fluid composition range of that class, serves as input for Stage 2.

The first part of Stage 2, Program Definition, compares the geothermal fluid composition range for each class with the geothermal plant system components in order to identify specific problems which would arise from the use of such geothermal fluids. Analogous problems are collected together and used as input for the next part, which involves verification of research projects. Here, the output from the previous part is compared with control methods in a matrix chart in order to determine control feasibility. The output from this chart forms the basis for defining research projects needed to solve problems relating to the use of geothermal fluids at selected sites in the United States. The proposed research projects are tabulated together with fiscal year 1977 projects already addressing some of the problems identified.

Although the work organization results in a comprehensive list of potential projects, it is not without problems of its own. These are listed here so that the reader might appreciate the reasons behind the decisions made in compiling the report.

First, the information on geothermal sites in the United States is currently insufficient for determining either the order in which they will be exploited or their relative importance to the attainment of significant exploitation of geothermal energy. However, a recent study by Reitzel[3] has been made of the economics of exploiting for power generation those geothermal resources listed by White and Williams.[1] Reitzel's study does allow some intelligent guesses to be made as to which resources show most promise at this time.

The implementation of projects proposed may result in significant technical advances which may alter the order in which the resources will be developed. In order to provide the best estimate of the relative importance of geothermal sites, a research effort is required that is beyond the scope of the report and inconsistent with the time restrictions imposed for its completion.

Second, information on the composition of geothermal fluids at sites in the United States is difficult to obtain and of variable quality. As indicated above, a separate project has been completed in which currently available information has been compiled. Much of the data from geothermal sites that have been drilled are proprietary and usually confidential. Without such information, it is difficult to implement research projects that address site-specific problems. Hence the reason for a general approach.

Third, it is questionable whether the chemical analysis of a geothermal fluid is sufficient to identify the problems resulting from the use of that fluid. Persuasive arguments might be advanced in support of direct implementation of tests in the field to identify problems associated with a particular geothermal fluid, rather than attempting to predict problems on the basis of brine composition ranges in any particular class.

Fourth, the matrixing process used in this study is difficult to implement because of the numerous options that result. Many decisions must be made which are necessarily based on insufficient background information. Therefore, the bases for the decisions are professional assessments rather than in-depth evaluations.

Fifth, the method used does not permit easy incorporation of problems intrinsic to the use of geothermal fluids in geothermal plants (that is, problems relating to the need to design for the use of a fluid which differs from pure water in its physical, thermodynamic, and transport properties.)

In spite of these difficulties, research and development projects tabulated in the report should serve as a useful basis for the formulation of research plans to solve problems relating to the use of geothermal fluids in geothermal plants.

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KINETICS OF SILICA PRECIPITATION FROM GEOTHERMAL BRINES

O. Weres, A. Yee, and L. Tsao

INTRODUCTION

Experience has shown that certain of the minor chemical components of geothermal fluids present the greatest obstacles to making this resource environmentally acceptable and economically viable.

In the past, the most immediate concern has been the release of highly toxic and malodorous hydrogen sulfide to the atmosphere. However, substantial progress toward resolving this problem has been made by the Pacific Gas and Electric Company and others operating at The Geysers field in California.[1] It appears that hydrogen sulfide emission will no longer be the limiting factor for the next generation of geothermal power plants.

The Geysers field produces dry steam. The technical difficulties encountered there have to do mostly with the control of trace gas emissions. The utilization of the hot water resource, which is more abundant, brings with it the problem of precipitation and deposition of various solids and colloidal materials from the brine.

Deposition within the production wellbores and surface equipment causes scaling problems. Wellbore scaling at the Cerro Prieto geothermal field (Baja California Superior) is severe enough to necessitate an annual reworking of each well. Scale deposition on the heat-exchange surfaces of proposed binary-cycle plants may force heat-exchanger overdesign and frequent outages for routine cleaning. The scale-forming materials of greatest concern are amorphous silica and silicates and carbonates. Deposition of sulfates and sulfides may also be important in some cases. The silica and sulfate scales are the most difficult to remove.

Large amounts of amorphous silica gel are deposited in the spent brine disposal conduits and ponds at Cerro Prieto and Wairakei (North Island of New Zealand). It is dealt with by periodically dredging the brine canals and, at Cerro Prieto, by periodically replacing the spent brine pipes.

Reinjection is not practiced in either of these areas, and there is good reason to believe that the colloidal and dissolved silica in the brine would cause severe plugging of reinjection wells. Indeed, brine injection experiments at Niland (Imperial County, California) have concluded that brine injection destroys the primary permeability of a well within days.[2] Sustained injection seems possible only when the well in question has large fracture permeability. This is mildly encouraging, but can hardly be relied on in general.

The chemical behavior of the scale forming carbonates, sulfates and sulfides is reasonably well understood. Carbonates and sulfides may be easily removed, and a variety of commercially available scale inhibitors are known to be effective against carbonate and sulfate deposition.

In contrast to this, very little is understood about the chemical behavior of silica in geothermal brines. The only methods available to remove silica scales are washing with caustics or acid fluorides and physical removal. The only means of silica scale inhibition that has been successfully demonstrated to date is brine acidulation,[3] which causes the silica to remain in the brine in the form of a colloidal suspension. Unfortunately, this relatively stable colloid is also quite capable of causing reinjection problems.[2] Also, the acidulation of the brine may cause severe corrosion problems in many circumstances. There is excellent reason to believe that ordinary scale inhibitors will prove ineffective against silica because of its amorphous and covalently bonded nature.

In general, amorphous silica and silicates present the greatest challenges of interpretation, prediction, and control in the field of industrial geothermal chemistry.

PROJECT GOALS

The major goal of this project is to develop a capability to quantitatively interpret and predict the behavior of silica in geothermal brines. We are using the full capabilities of both experimental and theoretical chemistry in this effort. The results we have obtained are of high scientific quality. Ultimately, we expect to reduce our conclusions to practical computer codes which will be employed to model silica chemistry within geothermal brine systems. Aside from the immediate utility of our work in geothermal resource utilization, we expect that it will also make a major contribution to geochemistry.

PROJECT TASKS

Review of the Literature of Silica Chemistry

This task was substantially completed during FY 1977. The information gathered in the course of this review and its first-order interpretation are presently being written up. At the time of writing (January 1978) most of this review existed in rough draft form. The German and Russian language literatures have been covered as well. A number of important sources in these languages have been found and appropriately summarized.

During FY 1978 our original results and conclusions will be integrated into this manuscript and the resulting work will serve as our final report and as a monograph on silica chemistry.

Development of Mechanistic Models of Silica Polymerization

In the course of our interpretation of the literature data we have constructed mechanistic models of the condensation reactions, which involve catalysis by hydronium, hydroxide, and chloride ions and hydrogen fluoride. These postulated mechanisms have helped define our experimental program. These models will be refined by comparison with our experimental results.

Theoretical Model of the Homogeneous Nucleation of Amorphous Silica Particles

A sophisticated statistical mechanical theory of the homogeneous nucleation of amorphous silica has been developed. It is based upon the Lothe-Pound theory of nucleation[4] and upon the "structuralist" variant of water theory.[5] A portion of it comprises a theory of the structure and thermodynamics of the amorphous silica surface. This portion of the theory has proved sufficiently general and powerful to enable us to reconcile a number of apparently unrelated experimental results. We will soon attain the ability to estimate the free energy of any molecular species or particle composed of silicon dioxide and water.

Our theory of nucleation now awaits final verification and reconciliation with the results of experiments now in progress.

Determination of Nucleation Thresholds

The homogeneous nucleation of a new phase generally occurs only at some value of the saturation ratio well above unity. In the case of amorphous silica nucleation, this value appears to be about two. We are presently determining the exact value over a range of temperatures. This information is absolutely essential, because the critical saturation ratio is a practical limit beyond which massive and completely unstoppable precipitation ensues. The values obtained will be employed to finalize the nucleation model described above.

Kinetics of Silica Deposition on an Amorphous Silica Surface

We will determine the rate of monomer deposition on colloidal particles of known surface area as a function of temperature, monomer concentration, pH, and concentration of various catalytic ions. This is the single most important part of our experimental program because it will lead us to the capability of predicting the rate of deposition of silica on most or all surfaces.

Theory of Ion Exchange on the Silica Surface and the Coagulation of Colloidal Silica

Preliminary theoretical models of these processes have been developed and will be improved further in the near future. If time permits, we will also carry out such experiments as may be indicated in this area.

Analysis of Practical Experience and Field Data

In parallel with our fundamental investigations of silica chemistry, we are interpreting the available data relating to the phenomenology of silica precipitation from geothermal brines. So far we have found evidence for the "critical supersaturation threshold" in the behavior of brines at Wairakei (New Zealand) and Heber (Imperial County), and have explained the chemical basis of the prevention of deposition of silica from acidulated Niland brine. (The drop in pH eliminates the surface ion exchange necessary for rapid coagulation.

Development of Practical Means of Dealing with Silica and Other Geothermal Deposits

Basic research oriented toward practical needs inevitably leads to new and unexpected practical insights. We have already proposed and laboratory tested the use of the unique thermomechanical properties of the "shape memory alloys" for scale control.[6] Other unpublished concepts are also being evaluated.

Another task of this project is to monitor possible secondary fluid decomposition during the heat-exchanger experiments to be conducted at Heber during July and August of 1978. This will be done by means of gas chromatographic and mass spectographic analysis of time series of secondary fluid samples taken from the facility.

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RESERVOIR ENGINEERING

The activities of the geothermal reservoir engineering group during fiscal year 1977 included: 1) working on the development of new techniques for analysis of mass and energy transport in geothermal reservoirs; 2) making contributions to DOE and the geothermal community toward understanding specific geothermal reservoirs, such as East Mesa, California; and 3) assisting DOE to formulate and implement a comprehensive plan for support of research in geothermal reservoir engineering in a broad sense. Details of these activities are presented in succeeding sections of this report; however, highlights and short synopses of these activities are given below.

An especially significant contribution during this past year was the development of a multiple-well, variable-flow well-test analysis capability. This capability permits analysis of data, taken under operating conditions, on pressure, flow rate, and time at wells penetrating a reservoir. ("Operating" conditions prevail when a system of wells is feeding an operating power plant.) This analytical capability obviates the need to shut down the plant or the wells in order to acquire data with which to evaluate both the transmissivity and storativity of a reservoir and the condition of particular wells. In other words, this capability greatly extends the scope of data with which to understand a reservoir and the wells that produce from and reinject into it.

A study of the consequences of different programs of injection of cool fluid into a geothermal well, followed by production of that well, was carried out. The analysis provides insight into the consequences that various schemes of injection and subsequent production have on temperatures within a reservoir and on the temperatures of fluids produced after a period of injection. Different arrangements of injection intervals and production intervals in the same well were studied, as were situations in which the reservoir was characterized by different distributions of permeability.

Studies of specific geothermal reservoirs (see Figure 1) included work not only at East Mesa, California, but also at Raft River, Idaho, Cerro Prieto, Mexico, and Serrazzano and Castelnuovo, Italy. Lesser efforts were carried out at Heber and Coso Hot Springs, California. Well testing to determine reservoir parameters was the principal activity at East Mesa. However, work there also led to the development and evaluation of geothermal well testing apparatus and test techniques (for instance, the James technique). Well testing to determine reservoir parameters was conducted at Raft River.

An international agreement for cooperative study of the Cerro Prieto field was signed in September 1977. Such an agreement permits the United States to participate in a comprehensive study of a reservoir of first-order importance for development of hydrothermal geothermal resources in the Salton Trough of the United States and for which an exceptionally good data base exists. Cerro Prieto, when fully documented, should serve as the prototype example of a hydrothermal geothermal resource. As such, it should be a principal guide to the exploitation of hydrothermal reservoirs in the United States.

Work in Italy was devoted to conceptualize geologic models and their approximation for use in computer codes for the Serrazano and Castelnuovo Zones of the Larderello region. The former is being examined to permit matching of approximately 40 years of production; the latter is being examined in order to model the response of a steam reservoir to injection. In both cases the utility of LBL-developed computer codes for reservoir simulation are being evaluated.

The reservoir engineering group also managed the ERDA geothermal reservoir engineering projects started under the NSF-RANN program and helped establish a comprehensive plan for support of all research in geothermal reservoir engineering. All NSF-RANN projects inherited by ERDA/DGE were continued and monitored by LBL. A comprehensive plan for research known as GREMP was generated and evaluated, and implementation was started. The two activities were united under the master plan and readied for continued implementation in fiscal year 1978.

A highly successful and well attended symposium on well testing was held in October 1977. This meeting brought together for the first time experts in hydrologic well testing, hydrocarbon reservoir testing, and geothermal well testing. The opportunity for these specialists to "compare notes" was an outstanding feature of the meeting and led to its extraordinary success.

Technique Development

VARIABLE-RATE MULTIPLE-WELL TEST ANALYSIS

D. G. McEdwards and C. F. Tsang

INTRODUCTION

LBL has developed a computer-assisted technique[1] for analyzing well test data that are not amenable to analysis by conventional graphical methods. The need for such a technique became apparent about two years ago when LBL was given well test data that reflected the effects of a strongly variable production rate. Subsequently, a computer-assisted least-squares matching technique was developed that could account for variable flow rate from one production well and could analyze observed pressure data for three reservoir parameters: kh (transmissivity), ϕch (storativity), and r_i (image well distance in the presence of a linear boundary). During 1977 the technique was extended to include the effects of wellbore storage and skin at the production well and the effects of two or more producing wells on the data collected in an observation well. Examples of these extensions developed in 1977 are given below and are intended to serve as a supplement to the examples given in last year's report.[2]

ACCOMPLISHMENTS, 1977

Wellbore Storage and Skin Effect

The wellbore storage parameter C, a known quantity, is used to calculate the rate of fluid flow from the reservoir to the well (the sandface rate). If the sandface rate is known, the skin factor (a measure of formation damage caused by drilling operations) may be estimated. The skin effect may be thought of as an increased resistance to fluid flow that causes a pressure drop between the reservoir and the well that is proportional to the sandface rate. Examples involving wellbore storage and skin are shown in the following sections. The wellbore storage example involves matching a known analytical solution, while the skin effect example involves analyzing production data taken in the Raft River Geothermal Field in Idaho.[2]

Constant Flow with Wellbore Storage

This verification problem relates to a well with significant wellbore storage but no skin (s=0). The change in the downhole pressure with time for such a system has been provided by Wattenbarger and Ramey.[3] In the hypothetical reservoir considered, kh = 484,300 md-ft and ϕch = 2.128 ft/psi and is pierced by a well with a wellbore capacity (C) of 1000 gal/psi. The well produces at a constant surface rate of 100 gpm. The drawdown history of the aforesaid well was computed using Wattenbarger and Ramey $P_D(t_D)$ values.[3]

The time-dependent variation of the sandface flow rate is presented in Figure 1. The analyses performed (Fig. 2) yielded kh = 485,000 md-ft and ϕch = 2.299 ft/psi.

Production Test on Well RRGE 3, Raft River Valley, Idaho

During this test the well was flowed for 193.5 hours. Dur to practical difficulties the flow rate could not be regulated properly during the first 20 hours of the test. The observed variable flow rate history is presented in Figure 3.

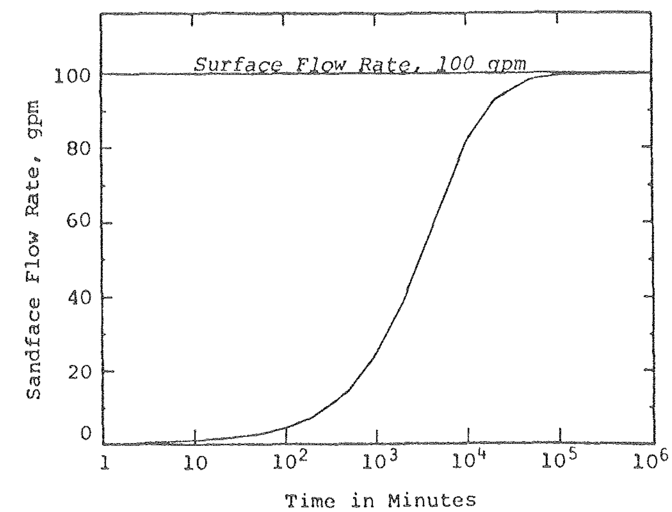

Figure 1. Sandface flow rate as a function of time.

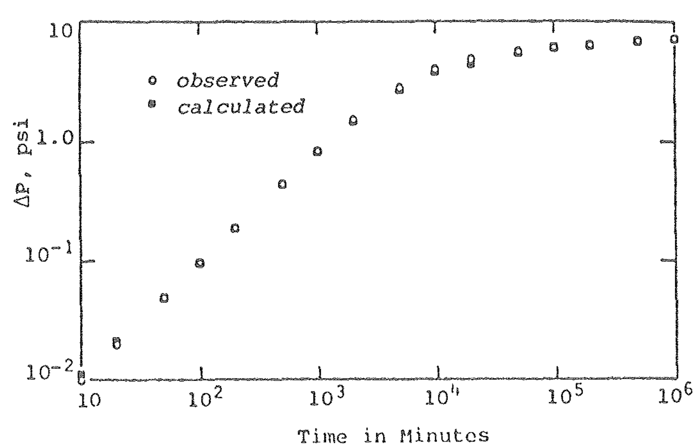

Figure 2. Computer-assisted match of predicted and theoretical drawdowns.

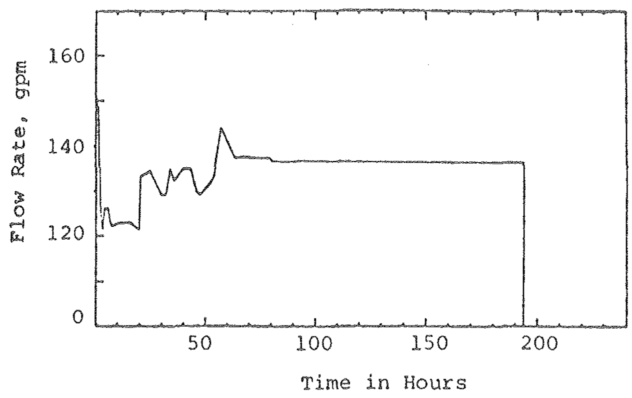

Figure 3. Production test on Well RRGE 3, Raft River Valley, Idaho; flow rate as a function of time.

In addition to the variable flow rate, the interpretation of the drawdown data collected during the test is complicated by the fact that Well RRGE 3 is a whipstock well, with three differently inclined legs, having bottoms ending at different elevations over a radius of roughly 400 ft. Furthermore, drilling operations indicated that each leg produced different quantities of water, suggesting that the formations pierced by each leg had different local permeability characteristics. The data interpretation which follows is therefore only tentative as far as the actual reservoir characterization is concerned.

Using the computer program, the data are analyzed with wellbore storage, C = 10 gal/psi, and skin effect, s. The full range of data of 0 to 328 hours is analyzed. Figure 4 presents results

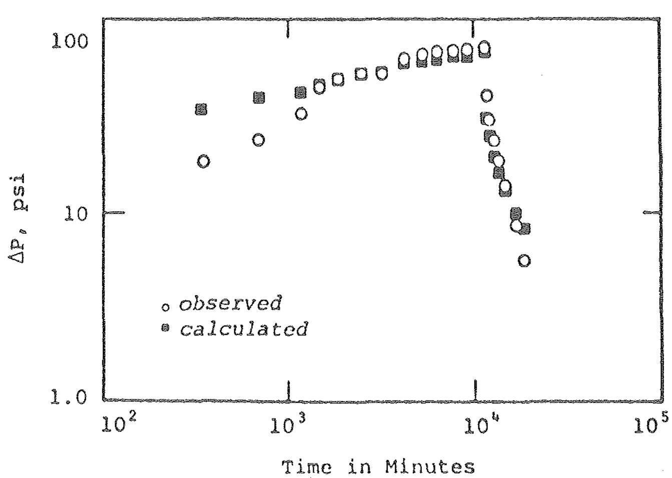

Figure 4. Production test on Well RRGE 3, Raft River Valley, Idaho; computer assisted match of calculated and observed drawdowns; 0 → 38 hrs, C = 10 gal/psi; s = -2.4.

typical of several analyses done. The reasonableness of the returned reservoir parameters for this analysis is good considering the unique nature of the well.

Many Producing Wells

Often observation data are influenced by more than one producing well. This is usually the case when an interference test is conducted in a reservoir in which other wells cannot be shut in because of economic or other considerations. The verification example given below demonstrates the technique's ability to successfully analyze such data.

Three Staggered Production Wells of Different Rates and Distances

The assumed reservoir properties are kh = 30,000 md-ft and $\phi ch = 1.0 \times 10^{-3}$ ft/psi. A plot of the observation-well pressure change and the distances and rates of each production well are shown in Figure 5. Using perturbed values (±5%) of the drawdown values an analysis was run, the results of which are shown in Figure 6. Agreement is quite good as seen by the returned values of kh = 30,000 md-ft and $\phi ch = 0.987 \times 10^{-3}$ ft/psi.

FUTURE WORK

We are currently extending this method of analysis to handle variable flow from a vertical fracture intersecting the wellbore. The analysis of many production wells in the presence of a linear boundary has not been implemented yet, but this presents no difficulty, since it merely requires

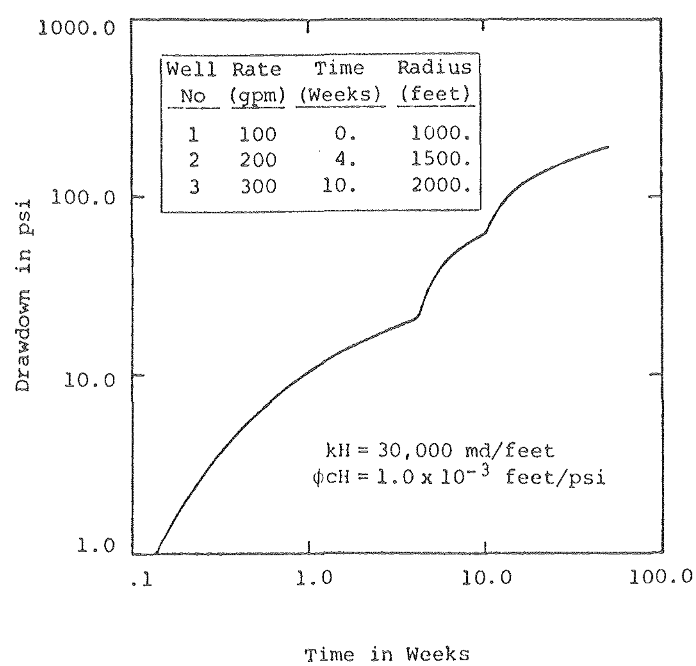

Figure 5. Three staggered production wells.

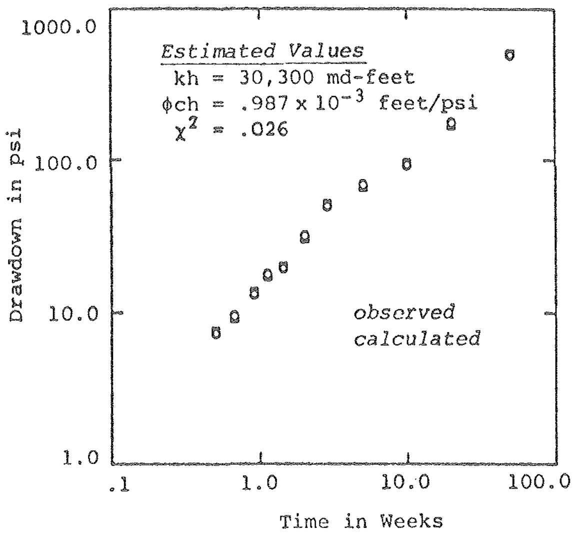

Figure 6. Three staggered production wells.

slight modification of the existing program structure. We also hope to extend the method to simultaneously analyze data from two or more observation wells in the presence of two or more production wells.

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ANALYSIS OF THE RESPONSE OF GEOTHERMAL RESERVOIRS UNDER INJECTION AND PRODUCTION PROCEDURES

M. J. Lippmann, C. F. Tsang, and P. A. Witherspoon

INTRODUCTION

A major problem facing geothermal energy development is the disposal of large quantities of relatively cool geothermal waste waters. Operators are reluctant to reinject these fluids because they could irreversibly cool the reservoir around the injection wells and affect nearby producing wells.

The project being reported here started in 1975. Its main objective is to establish ways to minimize the possible cooling and ground deformation effects resulting from reinjection of geothermal brines into liquid-dominated geothermal fields. Simplified models have been previously used to investigate the thermal effects of reinjection wells on neighboring producing wells[1] and the role of screening wells in multiple-well systems.[2] However, no studies have been made using more sophisticated numerical models to analyze the response of geothermal systems under different injection-production schemes.

ACCOMPLISHMENTS FOR 1977

The numerical code CCC (for Conduction-Convection and Compaction), developed at LBL, was applied to examine the response of a radially symmetric water-dominated geothermal system to injection and production from a single well.[3] Emphasis was placed on three problems:

1. Temperature recovery of a producing well after reinjection of cool fluid. The well was assumed to be used for injection for one year, after which it became a production well with or without a shut-in period in between. The effect of using a fully or partially penetrating well was also analyzed.

2. Consolidation of the reservoir, caprock, and bedrock during pumping. The effect of assuming different previous stress histories (that is, preconsolidation values) on the deformation of the system was studied.

3. Viscosity effects on transient reservoir pressure response. An analysis was made of the pressure changes resulting from a production-injection-production operation.

STUDY OF TEMPERATURE RECOVERY AFTER AN INJECTION PERIOD

A number of examples were analyzed to determine the effects of different injection and production schemes on the reservoir temperature distribution when one well is used first as an injector and later as a producer.

<u>Example 1: Fully Penetrating Well</u>

In this example, the well is injecting 2.5×10^6 kg/day of 100^oC water uniformly into a 100-meter-thick reservoir. The temperature distribution within the aquifer after 360 days of injection (total time, t = 360 d) is shown in Figure 1A.

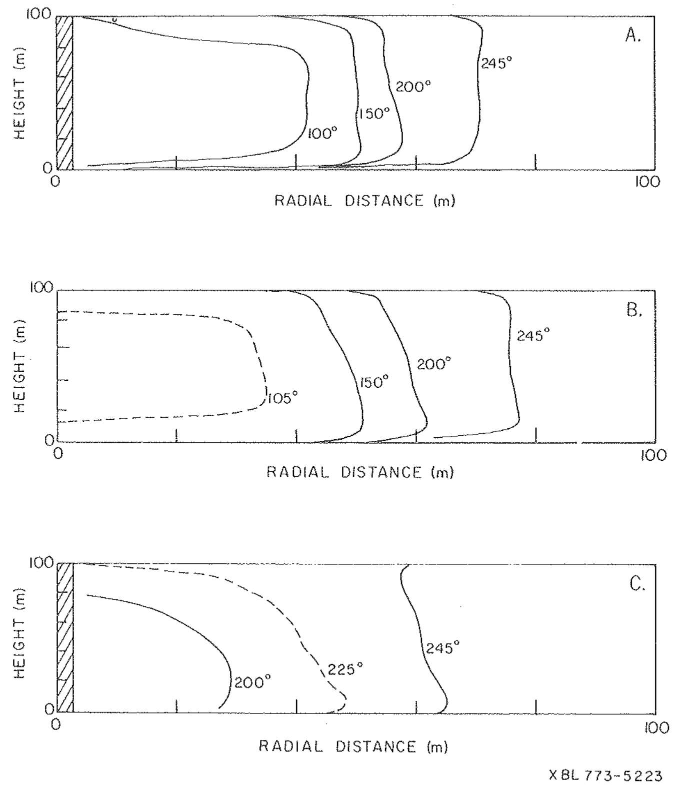

Figure 1. Example 1, temperature distribution in the reservoir: (A) after 360 days of injection; (B) after 360 days of shut in (t = 720 d); and (C) after 360 days of pumping (t = 1080 d). Hatched areas indicate production/injection intervals.

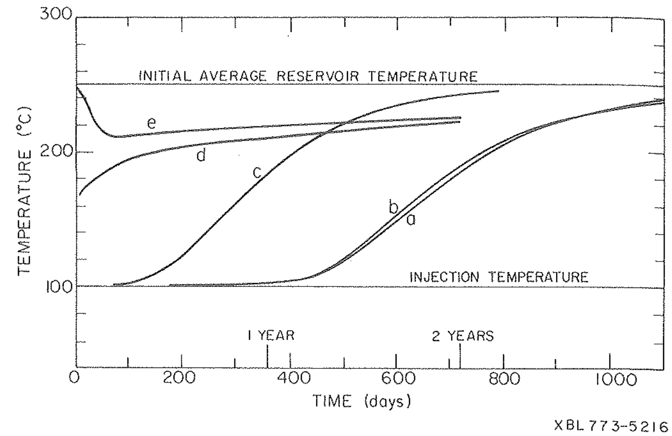

Figure 2. Temperature of produced water: (a) Example 1, full penetration with shut-in period; (b) Example 2, injection and production at the top zone with shut-in period in between; (c) Example 1, full penetration without shut-in period; (d) Example 3, injection at bottom zone and production at top zone without shut-in period; (e) Example 4, injection below low-permeability lens and production from above it without shut-in period.

If before pumping the well is shut in for a period of 360 days there is time for the high-pressure zone around the well to dissipate. The temperature after the shut-in period (t = 720 d) is given in Figure 1B. During the shut-in period the reservoir has gained some heat from the cap-rock and bedrock as water forced into them during the injection period flows back into the reservoir. After the shut in, production starts at the same constant rate (2.5×10^6 kg/day). The temperature distribution after 360 days of production (t = 1080 d) is shown in Figure 1C. Some of the cold water still remains in the reservoir. The temperature of the produced water is slowly increasing as a function of the production time, approaching assymptotically the original average reservoir temperature of 250°C (Fig. 2, curve a). If instead of shutting in the well pumping is started immediately after the injection period (t = 360 d), the temperature distribution after 360 days of production (t = 720 d) is not significantly different from that given in Figure 1C. This is also indicated by the temperature of the produced waters (Fig. 2, curve c).

Example 2: Partially Penetrating Well

Injection and Production from the Upper Part of the Reservoir

In this case, the well injects into and produces from the upper 40 m of the reservoir, at the same rate as in the previous example. The temperature profile after 360 days of injection is given on Figure 3A. It shows that the cold water has travelled more into the upper part of the aquifer and less into the lower part than in the full-penetration case.

After 360 days of shut in (t = 720 d) the temperature distribution (Figure 3B) reflects the effect of the colder (and heavier) water sinking and mixing with the hotter water below. Figure 3C shows the temperature after 360 days of production from the top 40 m of the reservoir (t = 1080 d). The temperature of the produced water is given in Figure 2, curve b. Clearly in this case the temperature recovery is similar to that of the fully penetrating well (Ex. 1).

Example 3: Partially Penetrating Well

Injection in the Lower Part, Production from the Upper Part of the Reservoir

This example differs from the previous one in that the injection is made into the lower 40 m of the reservoir instead of its upper part. In this way the cold water is pushed along the bottom of the reservoir and its higher density and viscosity slows down its migration towards the upper regions of the system.

Figure 4A shows the temperature distribution in the reservoir after 360 days of injection. As expected, most of the cold water stays at the bottom of the reservoir. If after injection the well is shut in for 360 days, only small temperature

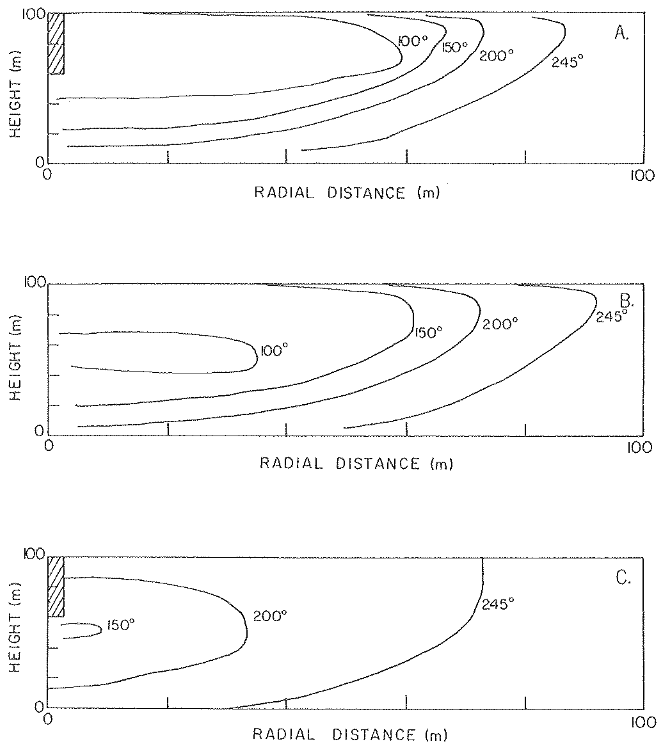

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Figure 3. Example 2, temperature distribution in the reservoir: (A) after 360 days of injection into the upper part of the reservoir; (B) after 360 days of shut in (t = 720 d); and (C) after 360 days of pumping from the upper part (t = 1080 d). Hatched areas indicate production/injection intervals.

changes are observed. The cold water is relatively immobile. Because there appears to be no advantage in shutting in the well, the case of immediate production after injection is analyzed. In this example, the pumping is done from the upper 40 m of the reservoir to minimize the extraction of cold water from the bottom. The temperature distribution after 360 days of pumping (t = 720 d) is given in Figure 4B. It indicates that the cold water is only slowly migrating toward the producing interval because of its high density and viscosity.

This scheme of injection and production at different levels results in pumped water temperature that is always higher than the injected water temperature (Figure 2, curve d). Because the cold water is slowly pumped out of the reservoir, the temperature of production, even though it is higher at the beginning, does not approach the initial average reservoir temperature as fast as in the two previous cases.

<u>Example 4: Partially Penetrating Well</u>

Injection into the Reservoir Below a Low Permeability Lens, Production From Above the Lens.

This case is intended to illustrate the dramatic effect of even a small lens of low permeability material on the temperature of the produced waters, when injection into reservoir is done below the lens and production is from above it. The only difference between this case and Example 3 is that a 20-m-thick, 25-m-radius lens of the same material as the caprock is present at the center of the system (Fig. 5).

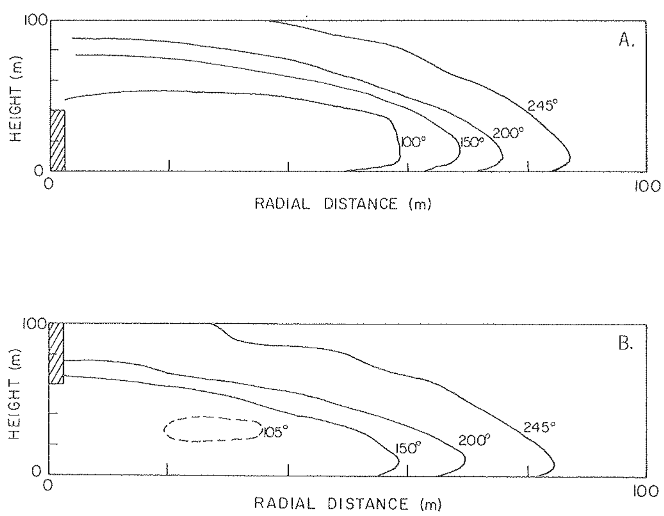

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Figure 4. Example 3, temperature distribution in the reservoir: (A) after 360 days of injection into the lower part of the reservoir; and (B) after 360 days of production from the upper part (t = 720 d). Hatched areas indicate production/injection intervals.

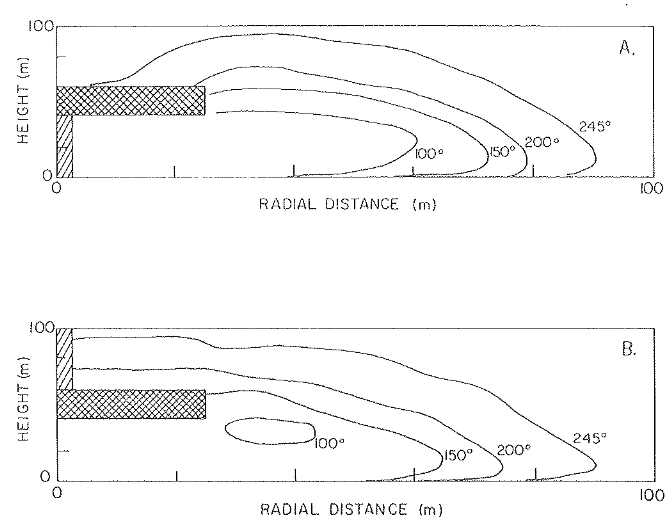

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Figure 5. Example 4, temperature distribution in the reservoir: (A) after 360 days of injection into the lower part of the reservoir; and (B) after 360 days of production from the upper part (t = 720 d). Hatched areas indicate production/injection intervals; cross hatched areas represent a lens of low-permeability material.

After 360 days of injection below the lens the temperature in the reservoir is shown in Figure 5A. The lens has greatly restrained the flow of cold water towards the upper part of the system. The injected water has moved along the bottom of the reservoir farther away from the well than in any of the cases considered before.

As in the previous example no advantage is expected from shutting in the system after injection. Therefore, production from above the lens is started immediately after the injection period. The temperature in the reservoir after 360 days of pumping ($t = 720$ d) is shown on Figure 5B. The temperature in the upper part of the system is higher than in Example 3 and the upward movement of the colder water is slowed down not only by its high density and viscosity but also by the presence of the low permeability lens. This is reflected by the temperature of the produced water (Fig. 2, curve e). The temperature drops slightly at the beginning, then stabilizes, and finally slowly rises after three months of production. It never drops below 210°C.

Remarks

These examples illustrate the importance of planning an injection operation if the wells are intended to be used later for production. The colder waste waters should be injected into the lower part of the geothermal reservoir and production should be made from the upper part. This will take advantage of the water density and viscosity variations with temperature. Most of the cold water, which is denser and more viscous than the warmer geothermal water, will tend to remain at the bottom of the reservoir. When production starts from the top, the warmer water will tend to move radially towards the well without large-scale mixing with the cold water from below. Example 4 illustrates the important effect of heterogeneity in the reservoir. Even a small lens of 25-m-radius greatly affects the temperature of the produced water, if injection is done below it and pumping from above it. The ultimate case would be a continuous layer of low permeability (aquitard) dividing the reservoir into two parts. In this case, the temperature of the upper part would not be affected appreciably if cold water is injected into the lower part. But no major recharge of the upper system would occur, resulting in larger pressure drops. From Figure 2 we can conclude that a well that has been used for reinjection will eventually regain its initial temperature. Its rate of recovery will depend on how the reinjection of cold water is made. If some initial drop of temperature does not affect its intended use, the produced water may be used immediately, assuming that the injection is made into the bottom followed by production from the top of the reservoir (Fig. 2, curves d and e). If an appreciable temperature change cannot be tolerated, some of the pumped water will not be adequate at the beginning, but after a period of time the temperature will approach its initial value. In this case a fully penetrating well will result in a faster recovery (Fig. 2, curve c). It has been shown that shutting in the well between injection and production periods will not greatly affect the temperature of the produced water.

STUDY OF CONSOLIDATION DURING FLUID PRODUCTION

Several cases were studied to obtain some insight on how to minimize compaction resulting from successive injection and production operations. It was found that the deformation of the system depended heavily on the properties assigned to the different materials. If the same properties were used, similar results were obtained when totally or partially penetrating wells were modeled. Rebound accompanied injection, but a final net compaction resulted from pumping because of the partial nonelastic response of the materials to changes in effective stress (that is, total stress minus pore pressure).

Further results[4] are presented in another part of this annual report, "Modeling Subsidence due to Geothermal Fluid Production."

STUDY OF EFFECT OF TEMPERATURE-DEPENDENT VISCOSITY ON TRANSIENT PRESSURE RESPONSE

The effect of temperature-dependent fluid viscosity on transient well-test analysis was investigated. A well is first pumped for five days (total time, $t = 0$-5 days); this is followed by five days of injection of 100°C water ($t = 5$-10 d); and finally the well is pumped for another 15 days ($t = 10$-25 d). The pressure changes obtained at the center of the reservoir, 1.5 m from the axis of the system, is shown on Figure 6B. The pressure decreases normally during the first pumping period ($t = 0$-5 d) and no temperature changes are observed. During injection the pressure increases as expected ($t = 5$-10 d) and the temperature drops almost immediately as the cold water is injected.

During the final period of production (Fig. 6B; $t = 10$-25 d) the pressure begins falling much faster than during the first period of pumping. The pressure stabilizes to an almost constant pressure value before continuing to decrease. The last part of the curve appears to be a continuation of the curve corresponding to the first pumping period. This response can be explained by studying the temperature and viscosity variation observed during this period (Figure 6A). During the first two days of the second pumping period the temperature remains low, then it slowly increases as the hotter water replaces the cold water being produced at the well. On the other hand, the viscosity of the fluid is high at the beginning and then rapidly decreases as the temperature rises.

For the same flow rate, the higher initial values of viscosity result in larger pressure decreases. As the temperature increases and the viscosity decreases, the pressure stabilizes and finally begins to drop as a nearly constant temperature is attained. After about eight days the temperature in the reservoir is similar to that prevailing during the initial pumping period ($t = 0$-5 d). This explains why, for later times, the pressure curve for the second production period is almost a continuation of the dashed curve corresponding to the initial period of production (Figure 6B).

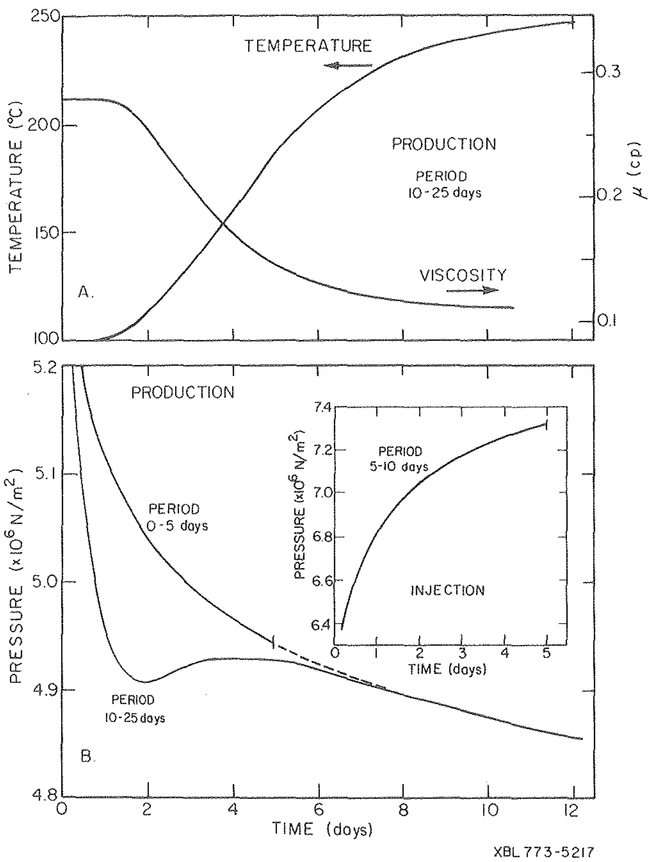

Figure 6. Effect of viscosity variation on pressure response. Plot of: (A) temperature and viscosity versus time (period of 10-25 days); and (B) pressure versus time for a point at the center of the reservoir, 1.5 m from the axis of the system.

If we assume that the pressure during the initial pumping period (t = 0-5 d) to be observed pressures during a normal well test, we can perform a typical constant-temperature Theis well-test analysis. We find that we reproduce the reservoir parameters correctly so long as we can use the density and viscosity constant corresponding to the average reservoir temperature. This justifies to a certain extent the application of usual pumping well-test methods to geothermal systems.

On the other hand, as discussed above, a very interesting pressure response curve is found when the well is pumped after a period of injection of colder water. This opens the possibility of using injection-production well tests to establish some of the thermal properties of the reservoir.

PLANNED ACTIVITIES IN 1978

1. The effects of regional water movement, chemical precipitation and anisotropy on the behavior of the production-injection wells will be examined.

2. Further studies of the type of pressure response resulting from temperature-dependent fluid properties, especially viscosity, will be made. Hopefully these studies will lead to the development of new well-test methods to establish the thermal as well as hydraulic parameters of a geothermal system.

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Field Studies

RECENT RESULTS FROM TESTS ON THE REPUBLIC GEOTHERMAL WELLS, EAST MESA, CALIFORNIA

T. M. Narasimhan, R. C. Schroeder, C. G. Goranson, and D. G. McEdwards

INTRODUCTION

Since early 1976, LBL has been involved in carrying out well tests on the the geothermal reservoir at East Mesa, Imperial Valley, California.[1] Between August and October 1977 further well tests were conducted in the geothermal wells located in the northern part of the field owned by Republic Geothermal Inc. The activities included production-well and interference tests and provided information on the reservoir parameters and reservoir geometry. The tests were conducted in cooperation with Republic Geothermal Inc.

DESCRIPTION OF THE TESTS

In all, seven wells were involved in the well tests; six of these belong to Republic and one to the U.S. Bureau of Reclamation. The locations of the wells are given in Figure 1. Two of these, well 38-20 and well 16-29, were alternately used as production wells and well 18-28 was used for disposal of the produced waters by reinjection. The rest of the wells were used as nonproducing observation wells. A brief description of the wells is given in Table 1.

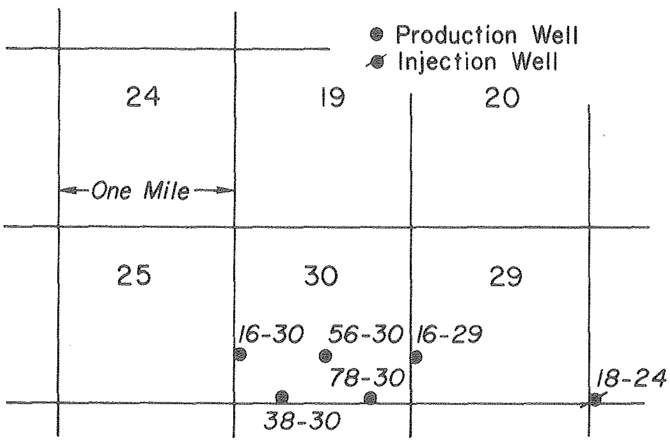

Figure 1. Location map of Republic geothermal well tests.

Tests 1 and 2 were short-duration production-interference tests which lasted a few days, and test 3 was a long-duration interference test which lasted several weeks. The details of the tests are summarized in Table 2. All the tests involved varying flow rates. The flow rates were measured by separating steam and water and then passing each through separate orifice meters. Pressure differentials in the observation wells (all of which are artesian) were measured with the help of sensitive quartz crystal pressure transducers. The flow data and pressure data were automatically recorded as printouts or strip charts.

RESULTS AND INTERPRETATION

All the tests conducted were characterized by variable discharges. At the outset, therefore, it became impossible to use the conventional type-curve matching procedures of analysis, which are generally based on fixed flow rates. Instead, a computer assisted curve-matching procedure recently developed at LBL[2] formed the backbone of all the interpretation.

The interference data collected during test 1 from well 56-30 (kh = 26,300 md-ft; $\phi ch = 4.5 \times 10^{-4}$ ft/psi) indicated the possible presence of a barrier boundary. The boundary could be represented by an equivalent image of well 38-30 located 4,600 feet from well 56-30 and 2,700 feet from well 31-1. In addition, both test 2 and test 3 brought to light the fact that well 16-30 did not show any pressure response to production from either well 16-29 or well 38-30. This is remarkable because well 56-30 (which is as far from well 38-30 as well 38-30 is from well 16-30) experienced a drawdown of as much as 21 psi during test 1 and 45 psi during test 3. The three pieces of data, namely the image well distances from 56-30 and 31-1 and the non-response of 16-30, strongly suggest the presence of a prominent, NNE-trending barrier boundary as shown in Figure 2. This boundary apparently does not conform to any of the geologically mapped faults, although its trend parallels those of inferred growth faults.

Table 1. Description of Republic Geothermal wells, East Mesa, California

Well	Total depth (ft)	Slotted interval (ft)	Net sand (in those intervals open during rest) (ft)	Date completed	Remarks
16-30	8,000	1,600 between 6,400 and 8,000 ft	1,116	July 1977	
56-30	7,520	2,225 between 5,300 and 7,550 ft	1,841	June 1977	
16-29	7,998	1,335 between 6,400 and 7,998 ft	827	Dec. 1975	
18-28	8,001	1,840 between 5,110 and 8,000 ft	231	Jan. 1976	No water entry between 6,400 and 8,000 ft
78-30	7,442	1,520 between 5,900 and 7,450 ft	1,257	Aug. 1977	
38-30	9,090	2,265 between 6,300 and 8,900 ft	499	Oct. 1975	Filled to 7,022 ft
31-1	6,175	760 between 5,400 and 6,200 ft	Not Available	June 1974	Owned by U.S. Bureau of Reclamation

Table 2. Details of Republic geothermal well tests

Test No.	Production well	Method of production	Flow rate (gpm)	Pressure measurement	Date	Observation wells and instruments 1	2	3	4
1	38-30	Valve* control	Step-wise variable 500, 750 900, 500, 225	Sperry Sun down-hole pressure monitor	July 14 to July 18, 1977	56-30	16-29	31-1	
						←— Paro Scientific well-head transducer —→			
2	16-29	Valve* control	Variable 200 to 700	Denver Research Institute and Sperry Sun down-hole pressure monitor	July 26 to July 30, 1977	16-30	56-30	31-1	
						←— Paro Scientific well-head transducer —→			
3	38-30	Downhole pump	Variable 200 to 1,000	None	August 22 to Oct. 5, 1977	16-30	56-30	78-30	31-1
						←— Paro Scientific well-head transducer —→			

* Natural, well-bore flashing flow

The production well data collected during test 1 suggested a kh of approximately 25,000 md-ft for the reservoir in the vicinity of well 38-30. In addition, the data also indicated a negative skin for well 38-30.

Interference data collected during test 3 from well 31-1 yielded kh, ϕch, and image well distances comparable with those obtained during test 1.

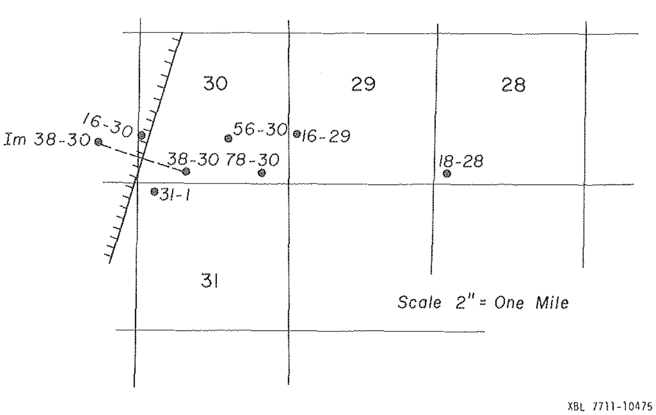

Figure 2. Inferred presence of hydrological barrier boundary for Republic geothermal well tests.

However, data from well 56-30 indicated somewhat lower kh and lower image well distance (see Table 3) than the first test. It may be noted here that at the start of test 3, the reservoir was still recovering from the effects of wells 38-30 and 16-29. The discrepancies mentioned may be attributable to the buildup effects of 16-29, which were ignored during the interpretation.

Interference data collected from well 78-30 during test 3 indicated anomalously low kh values of 10,400 md-ft for the reservoir between wells 38-30 and 78-30. The maximum pressure drop observed in well 78-30 during the test was about 3 psi, although computations showed that one would have normally expected drawdowns of the order of 12 to 15 psi. The reasons for this are being studied. From borehole logs and cores it appears that well 78-30 has sands of quality and thickness comparable with those in well 38-30. It is therefore of particular interest to adequately explain the low value of kh inferred between wells 38-30 and 78-30.

The estimates for the reservoir parameters obtained from the three tests are summarized in Table 3. This table also contains estimates of kh values obtained from borehole logs. As can be seen, a reasonable agreement exists between the current and previous estimates. In general, the reservoir below the Republic Geothermal lease has a kh of approximately 30,000 md-ft.

PLANNED ACTIVITIES FOR 1978

In response to a request from the U.S. Bureau of Reclamation, LBL will continue well testing at East Mesa to better understand the geothermal reservoir.

Table 3. Summary of test results from Republic geothermal wells

Well	Test 1 (38-30 producing)	Test 2 (16-29 producing)	Test 3 (38-30 producing)	Previous estimates
38-30	kh = 24,800 md-ft			Borehole logs (Intercomp): □kh = 44,000 md-ft
		--	--	Build-up test (Intercomp): □kh = 41,700 md-ft
	$\phi c h r_e^2$ = 1.36 ft^3/psi			Interference test (LBL): □kh = 29,500 md-ft
56-30	kh = 26,300 md-ft		kh = 23,600 md-ft	
	ϕch = 4.5x10^{-4} ft/psi	To be analyzed	ϕch = 7.89x10^{-4} ft/psi	
	r_i = 4,600 ft		r_i = 3,500 ft	
31-1	kh = 35,400 md-ft		kh = 31,700 md-ft	
	ϕch = 2.07x10^{-3} ft/psi	To be analyzed	ϕch = 2.4x10^{-3} ft/psi	
	r_i = 2,660 ft		r_i = 2,450 ft	
16-29	kh = 21,800 md-ft			Borehole logs (Intercomp): □kh = 30,000 md-ft
	ϕch = 2.36 x 10^{-3} ft/psi	--	--	Build-up test (Intercomp): □kh = 34,700 md-ft
78-30	--	--	kh = 10,400 md-ft	
			ϕch = 6.68x10^{-3} ft/psi	
			r_i = 3,300 ft	

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COOPERATIVE INVESTIGATIONS AT THE CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO

M. J. Lippmann, A. Mañon M., J. E. Noble, H. A. Wollenberg, N. E. Goldstein, A. Mazor, M. Wilt, and P. A. Witherspoon

INTRODUCTION

On July 21, 1977, the Comisión Federal de Electridad (CFE) of Mexico and the U.S. Department of Energy signed an agreement to conduct a cooperative study of the Cerro Prieto Geothermal Field, located approximately 20 miles south of Mexicali, Baja California, Mexico (Fig. 1). U.S. participation under this agreement is being coordinated by the Lawrence Berkeley Laboratory (LBL).

The cooperative project incorporates studies of the geologic, hydrogeologic, geochemical, and geophysical setting of the geothermal field, as well as its reservoir engineering and subsidence characteristics.

Operating since 1973, Cerro Prieto is the only water-dominated geothermal field generating electric power in North America. CFE, which manages

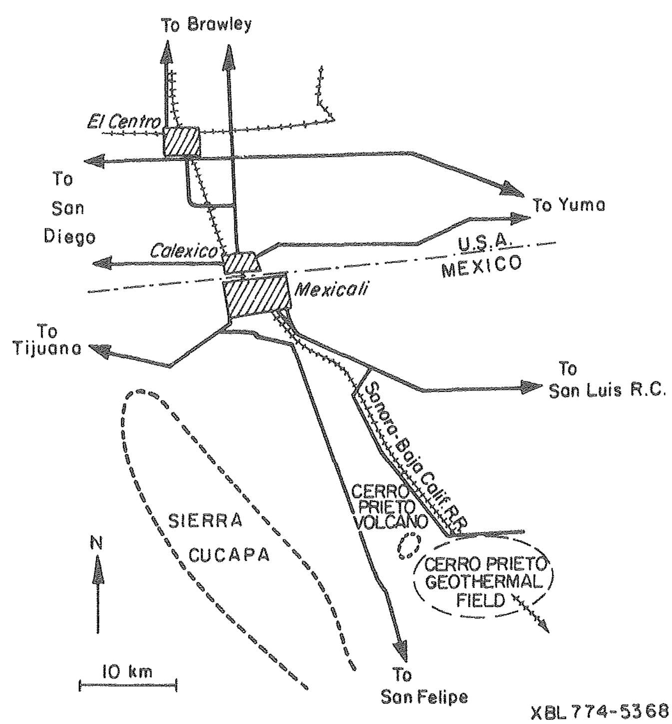

Figure 1. Location of the Cerro Prieto geothermal field.

the field, plans to expand the power output from the current 75 MW to 150 MW in mid-1979. In 1982 a 30-MW low-pressure turbine will be installed. It is estimated that by 1984 the total generating capacity of the field will reach 290 MW. An intensive drilling program of new production and step-out wells began in December 1976 to provide steam to the planned power plants. By the fall of 1977, 40 deep wells had been drilled in the area (Fig. 2). Some 16 of these wells were supplying a total of about 750 tons of steam per hour to the power plant to generate the present 75 MW.

The objective of the Cerro Prieto project is to develop a thorough understanding of the nature and magnitude of the energy source and to determine the subsurface impact of the exploitation of this geothermal system. An understanding of the behavior of the Cerro Prieto field can be applied directly to the several geothermal areas already identified in the neighboring Imperial Valley, in southern California.

ACTIVITIES IN 1977

Geologic, Hydrogeologic, and Geochemical Studies

The collection of available data on the Cerro Prieto, originally initiated in 1975, continued in 1977. The information was placed in an open-file data bank and became available to the geothermal community for independent study. A report[1] was issued documenting the holdings of the data bank as of April 1977.

Geophysical well logs, temperature logs, and production and geochemical data were analyzed to develop a preliminary model of the structure of the geothermal system.[2] Figure 3 shows the major lithologic units that have been delineated by manual well-log correlation and an auto-correlation computer program. The figure shows only the peripheral wells of the producing field and outlying exploration wells. As a result of this correlation it was postulated that the field was

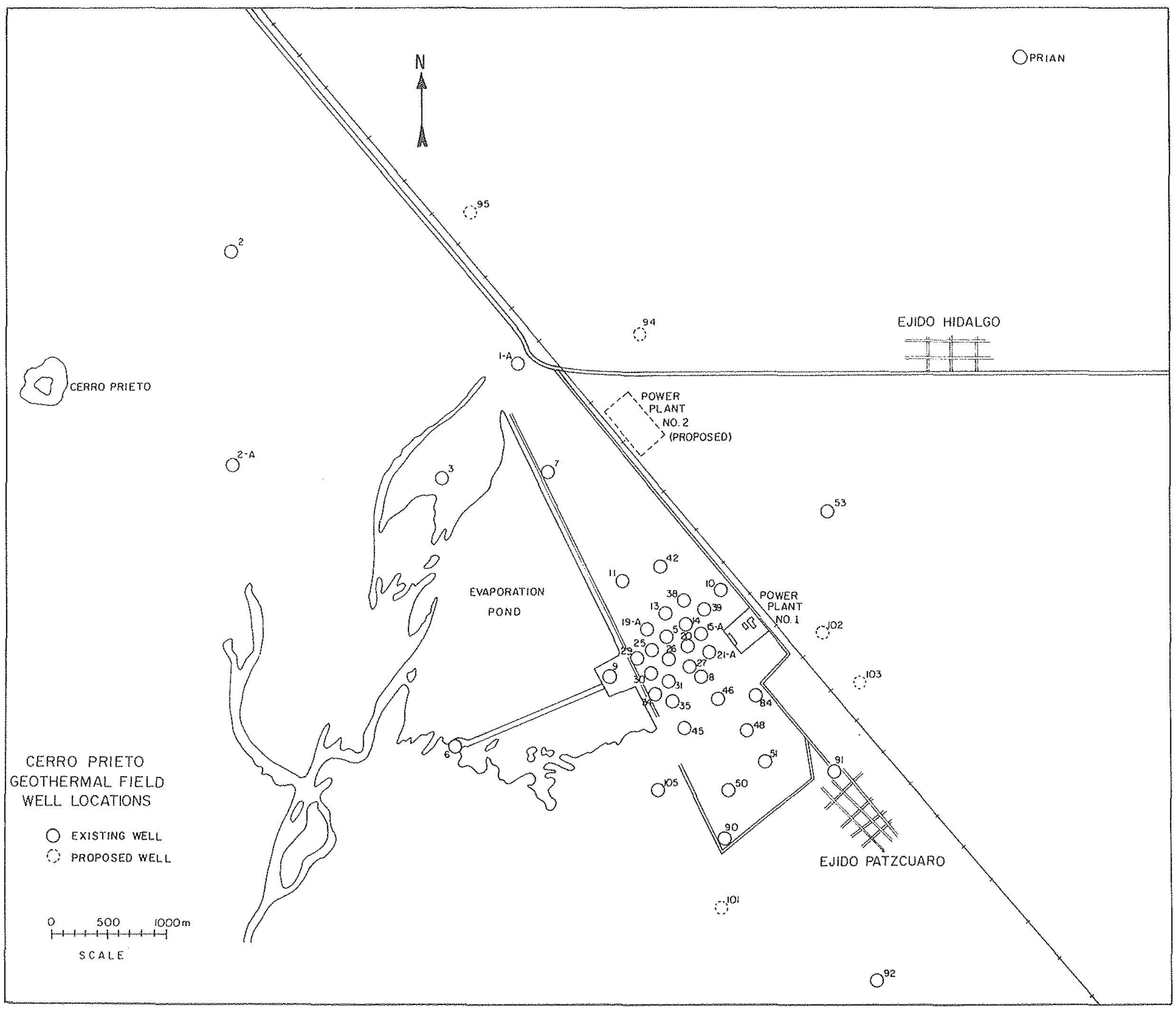

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Figure 2. Location of wells at the Cerro Prieto geothermal field (as of October 1977).

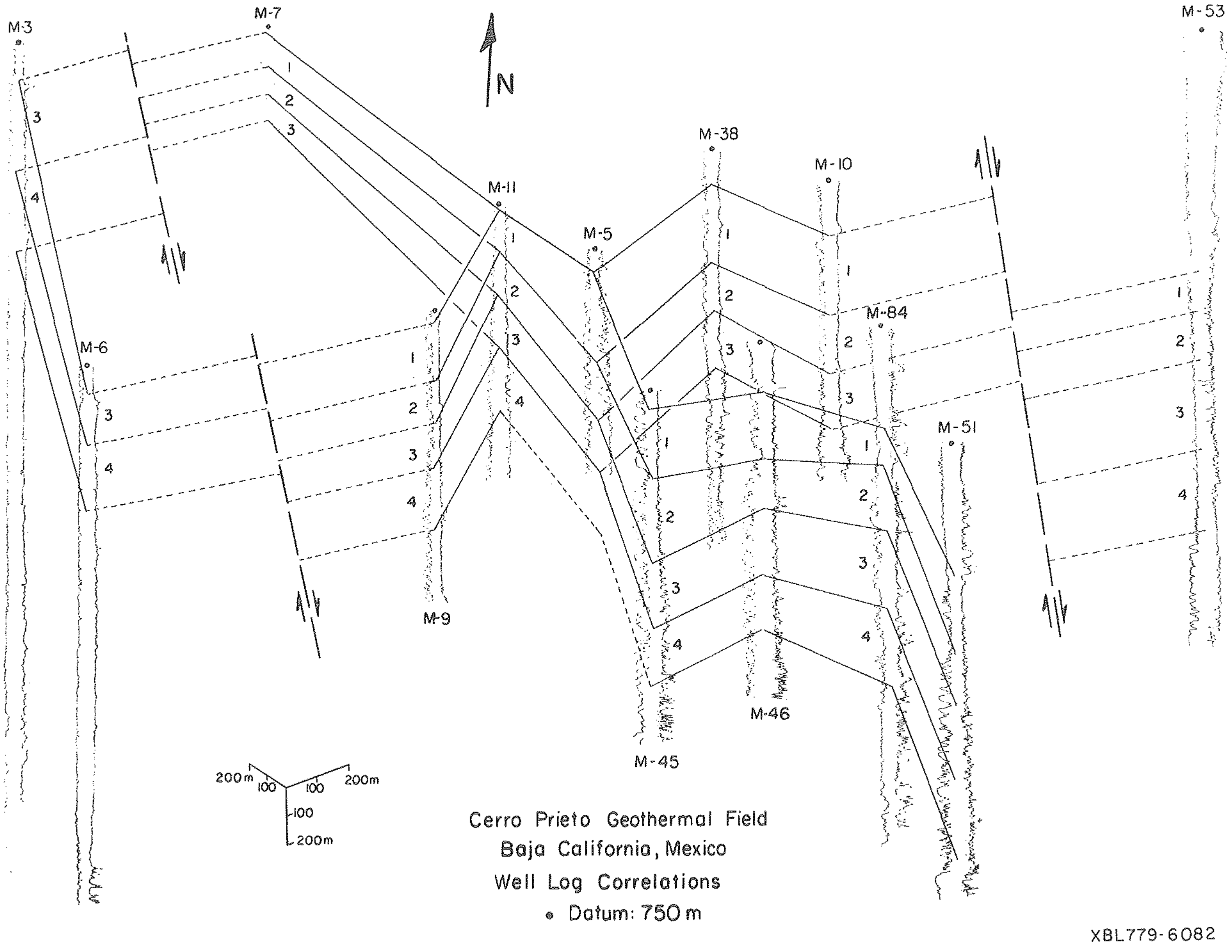

Figure 3. Major lithologic units delineated by well-log correlations.

bounded by two northwest-trending normal faults, down-thrown to the east. A review of fluid geochemical data[3] defined trends that were in general agreement with the structural division of the field into three distinct blocks (Fig. 4).

At a technical workshop held in September at LBL, all groups participating in this international project presented the results of their work and described their plans for the immediate future. After the two-day meeting, schedules and activities for the following months were agreed upon among the workshop participants.

Geophysical Studies: Self Potential

An orientation self-potential survey was conducted in December 1977 by R.F. Corwin assisted by two CFE geophysicists.[4] Two nearly orthogonal lines, each about 11 km in length, were run across the field. Line A-A', oriented northwesterly, parallels the trace of the Cerro Prieto fault. Line B-B' runs in an irregular northeasterly direction and passes over the producing part of the field a short distance north of the plant.

The survey was run using a "leapfrog" technique, in which a fixed length of wire (100 m on B-B' and 150 m on A-A') was dragged along the survey line. Electrodes at either end were alternated with each new reading to minimize the effects from accumulated errors due to electrode instability. A stationary electrode array and strip-chart recorder monitored the voltage variations from telluric currents and man-made transients. Because of the high conductivity neither effect was large enough to degrade the self-potential measurements.

On both lines a large-amplitude, long-wavelength anomaly was detected. Because the data may be subject to severe cumulative error and must be checked by means of additional field work, it is difficult to draw firm conclusions. However, on both lines the segment of steep negative gradients is closely associated with the producing field.

Geophysical Studies: Resistivity

Results from 30 Schlumberger array expanders obtained by a CFE geophysical crew along Line A (Linea Solfatara), were interpreted[5] by means of a

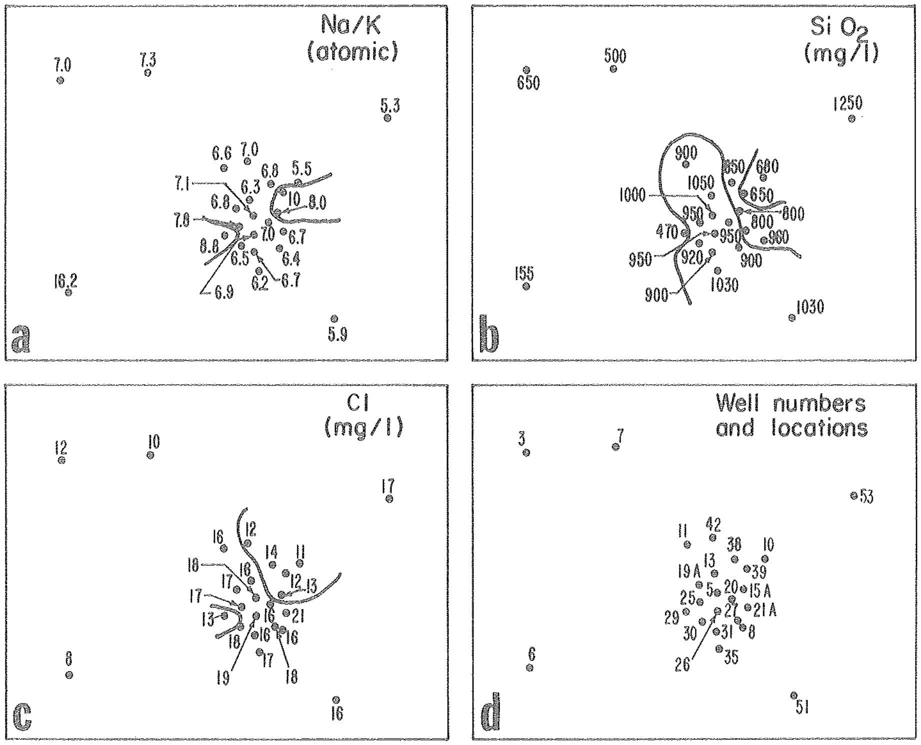

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Figure 4. Division of the field into three distinct areas based on geochemical data: a, Na/K ratio distribution; b, SiO_2 concentration distribution; c, Cl concentration distribution; and d, index map of wells analyzed.

two-dimensional modeling program developed at the University of California.[6,7] Current electrodes were expanded to maximum separations of 10 km and the arrays were centered over a linear distance of approximately 20 km. The survey line begins near the Sierra Cucapa, on the southwest, and extends northeastward across the Mexicali Valley, passing by the south edge of the Cerro Prieto volcano and crossing the northern end of the established geothermal field. The line extends well out into the Valley, ending 15 km from the trace of the Cerro Prieto fault.

Geophysical Studies: Gravity

Existing gravity data for part of the Mexicali Valley, including the Cerro Prieto geothermal field, were interpreted by means of a three-dimensional, two-layer inversion program. Using the gridded Bouguer data (Fig. 5), the computer program estimates the depth to basement or, usually, to some other density-contrast interface. In the computer code, the basement is approximated by many rectangular prisms, each one centered beneath a grid point. Depth to each prism is the variable sought for a specified overburden-basement density contrast. The best estimate of density contrast, hence of first layer thicknesses, is the value that satisfies all or most of the following: agreement between the zero first-layer thickness and exposed basement, agreement between calculated basement depth and a drill-hole intercept, and agreement between basement depths and the results of other geophysical surveys.

For a limited range of density contrasts tested, 0.2 g/cm^3 gave reasonably close results, although this value may be too large. Nevertheless, the analysis gives a picture of the major structural features in the area (Fig. 6):

1. The north-northwesterly trending Cerro Prieto fault is clearly indicated.

2. There is evidence for several northwest-trending faults, one of which (the so-called Delta fault) crosses the south end of the geothermal field and may be a structural boundary of the field.

3. The presently producing part of the field is located on a basement high which may be either a horst of basement rock or a shallow zone of densified sediments. Information from core samples and the resistivity interpretation suggest that the latter may be the correct cause.

4. The basement high northwest of the field correlates closely with an aeromagnetic anomaly. A common source--an intrusive igneous plug--is suggested on the basis anomaly correlation and similar source depths.

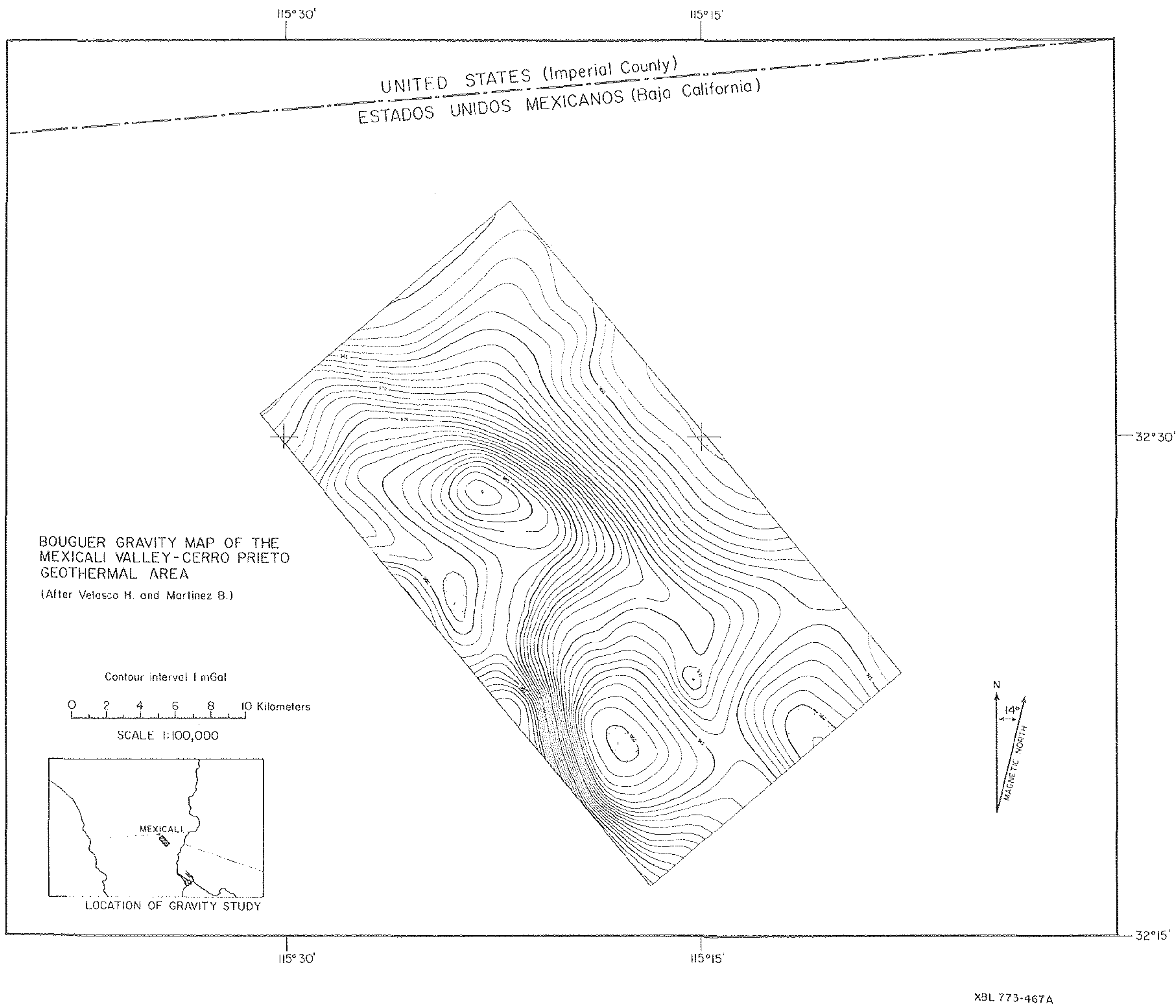

Figure 5. Bouguer gravity map of part of the Mexicali Valley around Cerro Prieto.

LBL performed no new gravity field work in 1977, but CFE installed a network of 40 permanent gravity monuments over and around the field that were tied into CFE's second-order-level network. Additional leveling and precision gravity measurements are planned to furnish baseline information needed to monitor subsidence and subsurface changes in mass due to the imbalance from production and recharge into the geothermal field.

PLANNED ACTIVITIES FOR 1978

Geology, Hydrology, Reservoir Engineering

In addition to coordinating the United States participation under the Cerro Prieto agreement, LBL will perform the following tasks:

1. Data will be collected, analyzed, and evaluated, to prepare updated geologic and hydrogeologic models of the geothermal system.

2. Well-tests and general reservoir engineering studies will be made to define the geometry, physical characteristics, fluid capacity, recharge capability, production ability and energy longevity of the reservoir.

3. Computer simulation studies will be made to study the behavior of the system under different exploration plans, to predict the magnitude of subsidence effects, and to evaluate the effects of reinjection of geothermal brines on the overall behavior of the reservoir.

4. Thermal properties and flow and storage capacities of reservoir rocks will be determined at reservoir temperatures and pressures in tests on representative core samples at the University of California's Berkeley campus. The mineralogy of the same cores will be determined at the University's Riverside campus.

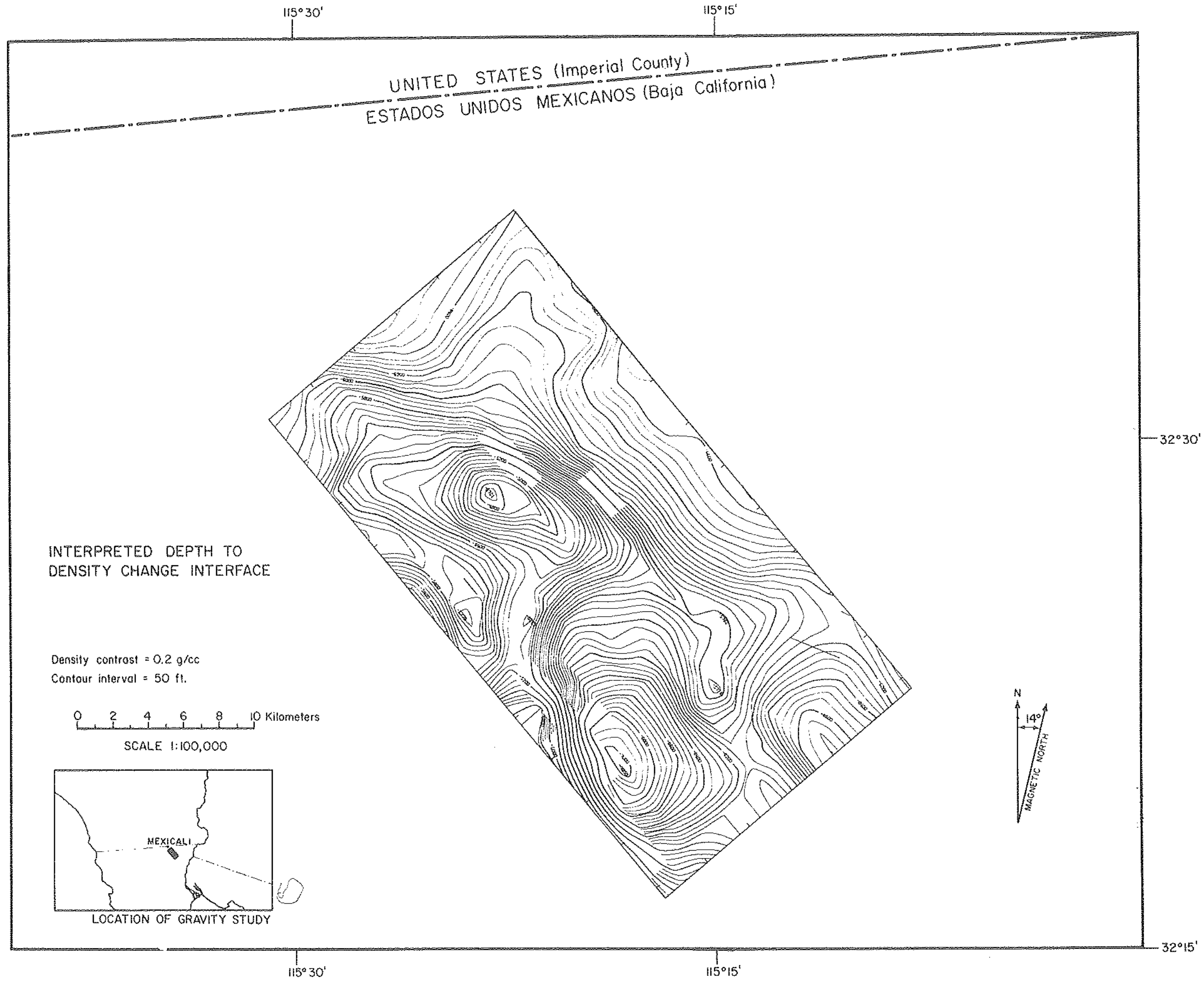

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Figure 6. Depth-to-the-basement calculated from the Bouguer gravity data.

Geophysical Studies: Self Potential

Additional self-potential surveys will be conducted to define the anomaly found over the field and to determine if cumulative errors are present in data already collected. This work will involve LBL, but eventually the self-potential work will become solely a CFE effort with LBL in an advisory position.

Geophysical Studies: Gravity

Precise gravity measurements, corrected for tidal variations and local sea-loading effects, will be made at about 40 monuments installed over and around the field. The measurements will be tied to an established gravity base station in Mexicali and will be repeated at six-month intervals. For each set of gravity measurements, CFE will perform a second-order survey. Changes in gravitational attraction and land elevation will be analyzed to identify any net mass changes within the reservoir during the production life of the field. Because of the long term of these measurements, responsibilities for data acquisition and interpretation will be transferred to CFE.

Geophysical Studies: Resistivity Surveys

LBL and CFE will install a permanent set of current electrodes in a long line over the field and perform a careful dipole-dipole survey. Similar surveys will be repeated thereafter at intervals to determine if changes in formation resistivities occur and if they are related to changes in temperature, chemistry, or flow rate of the fluids being produced.

Geophysical Studies: Magnetotelluric Surveys

A number of magnetotelluric (MT) stations will be occupied along a line normal to geologic strike and passing over the field. The purpose of the work will be: to determine the usefulness of MT for delineating major basement and crustal structure, to relate the findings to the geothermal regime, and to compare the results to those of other geophysical surveys.

Geophysical Studies: Seismic Investigations

The LBL 12-channel, FM-telemetered, portable seismic network will be set up near the field in various arrays. Microearthquake activity in the area of the Cerro Prieto fault will be measured and related to active faulting and regional stresses. P- and S-wave velocity and attenuation variations in the area over the field will be measured and, if possible, related to the field boundaries and geology.

Conference

A technical progress meeting of those working on the Cerro Prieto project will be held in Mexicali in the spring of 1978. A general symposium on results of Cerro Prieto activities will be conducted in Baja California in the autumn.

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EVALUATION OF GEOTHERMAL WELL TESTING EQUIPMENT

R. C. Schroeder, T. N. Narasimhan, and C. G. Goranson

INTRODUCTION

The equipment necessary for successful geothermal well measurements includes devices used at the wellhead, downhole equipment, and recording devices. Wellhead equipment includes devices to contain the hot fluids and measuring devices. The downhole equipment is used to provide measurements inside the geothermal wellbore to its entire depth. The recording equipment includes signal transmitters, detector-tranducers, chart-recorders and printers.

TRANSIENT PRESSURE MEASUREMENTS

When a geothermal well is flowed, the bottom-hole pressure declines from its static value. When the flowing well is shut in, the bottom-hole pressure builds up to an equilibrium value. These transient bottom-hole pressures can be analyzed (using reservoir models) to give approximate values of both the nearby reservoir properties (such as permeability, porosity, geometry, and fracture size), and the well characteristics (such as skin and wellbore storage effects).[1] The equipment needed for measuring bottom-hole pressures in hot (150-350^{o}C) geothermal wells with precision and speed is not available from the related oil and gas industries. Currently, equipment capable of responding quickly cannot survive the high temperatures in the well, and equipment capable of functioning at high temperatures does not have sufficient speed and accuracy. In addition to making measurements in flowing wells, it is also desirable to measure transient pressure behavior at shutin wells during a time when nearby wells are flowing. In this case measuring the bottom-hole pressure is not absolutely necessary, since only pressure differentials are needed in the analysis for the average reservoir parameters. This type of measurement can thus be made either at the wellhead (if the well is artesian), or downhole, below the water level. Often, the latter cases allow the use of equipment that is highly accurate but cannot survive the extreme environment at the bottom of the wellbore.

During fiscal years 1976 and 1977, the LBL reservoir engineering group evaluated available equipment and either modified or built prototypes for well measurements. These activities have been carried out in cooperation with several government agencies and private companies which were involved in the geothermal well testing. A few of the devices used for pressure transient measurements are reviewed below.

MEASUREMENT EQUIPMENT

The most sensitive downhole pressure-sensing device is the Hewlett-Packard quartz transducer.* This device uses two separate quartz crystals-- one resonating in a reference medium, the other in a buffered measurement mode. This device can provide a sensitivity of about 0.002 psi, which is less than the random noise level in most geothermal wells. The sensitivity is well within the earth tide levels of about 0.1 psi. The usual temperature limit of this downhole probe is about 150°C, although the device has functioned for short times at 170°C. The major problem with the equipment has been intermittent and unusual noise, which completely obscures the smaller signals. An effort was made to determine the origin of the noise and in the process, cable, electronic, telluric, and manmade electrical noises were all eliminated as the source of the problem. It was finally observed that the tool was extremely sensitive to temperature differences between the sensing crystal and the reference crystal.

Although these two crystals are only separated by about 10-15 cm (inside the stainless steel body), a touch of a finger (at room temperature) on the tool housing near the reference crystal causes enough of a thermal difference between the crystals to produce unacceptable noise levels. When the tool body is sheathed in a copper tube, which is clamped snugly to the stainless steel outer shell, all noise completely disappears and the tool meets the design sensitivity of 0.001 to 0.002 psi. Clearly, such a solution is unacceptable in geothermal wells due to the highly corrosive nature of the brine. It is possible that a more fundamental solution to the problem may be found, but we have not yet explored any further possibilities. This tool has been used successfully in measurements made at relatively low temperatures (≈145°C),[2] and the only interpretation is that there were no thermal gradients between the crystals. In general, this cannot be assumed.

A less sensitive method of measuring downhole pressure transients is the Sperry Sun system. This approach uses a capillary tube made of stainless steel to communicate with the bottom-hole conditions. The tube is pressurized with gas (usually N_2) to the downhole value minus the small gas head. There is a chamber at the downhole end of the well with an inner diameter that is large compared with the tubing. This reduces the movement of the gas-water interface, when the interface is in the chamber. At the surface, the pressure is monitored with a Bourdon-type mechanism, which has a sensitivity of about 0.2 psi. Because all recording equipment is at the surface (at ambient temperature), this approach can be used at any downhole temperature.

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the Department of of Energy to the exclusion of others that may be suitable.

One of the problems with this system is the acute sensitivity of the gas-filled tube to temperature changes. Often at geothermal sites, the diurnal temperature variations at the recorder are 10-15°C. These variations cause pressure changes in the capillary tubing between the well and the recorder of up to 20 psi. Even when the tubing and the recorder are heavily insulated, the tubing still has large temperature-induced diurnal noise. One possible solution is to put the equipment in a cooled compartment. However, the tubing, winch and reel, and recorder are too large to make this practical. And heating the equipment to maintain a constant temperature is also impractical.

A second problem in flowing wells is that the temperature of the fluid at the wellhead changes with different flow rates. Because change of rate is an important part of most well tests, these tests often show temperature changes. Such changes are primarily due to heat lost to the upper (cooler) formation while the well is flowing at different rates and flash points. Temperature transients occur in the downhole tubing following rate changes. These transients can amount to several psi. Because the Sperry Sun is readily available and has unlimited temperature applicability, methods of detecting the true signal from the measured value in the presence of thermal transients are currently being studied.

A third problem associated with the gas-filled capillary is the slow response of the tube to a step function input. This is due to the large viscous effect in capillary tubes having small diameters. This problem has been partially solved by using 0.054-in. inner-diameter tubing instead of the thicker-walled 0.024-in. tubing. Both of these tubes have the same outer diameter as the standard wireline, 0.125-in. Additional studies are underway to improve the transient response of these long tubes (4,000 to 8,000 ft). A minor problem, although severe in consequences, is the failure of the tubing due to hydrogen embrittlement or work hardening. The latter occurs when the tubing is used in wells flowing at a high rate. This problem can be reduced appreciably by using heavy weights to stabilize the chamber and tubing in the highly turbulent well flow. This solution requires the use of very tall wellhead lubricators and powerful winches, but has been completely successful at rates above 600,000 lbs/hr.

One final pressure transducer of interest is made by the Paroscientific Corporation. This is a quartz crystal device, which can be used at temperatures up to about 180°C. Because the device is electronic, its response is excellent but it is limited by the temperature tolerance, and in addition, it is accurate only to a fixed fraction of the full-scale applicability. Thus large pressure ranges (>1000 psi) cause transducer sensitivities >0.1 psi, and this does not allow detection of earth tides. When this device is used either in the underwater configuration or with short lengths of capillary tubing, it can provide interference data that are extremely stable and sensitive to all transient signals.

In addition to the equipment described above, the reservoir engineering group has used and modified equipment and techniques for all phases of measurements in geothermal wells, including downhole sampling, flow rate measurements, temperature measurements, and automatic recording and collection of data. Because the measurements have been carried out in cooperation with the geothermal leaseholders, government agencies, and private companies, our equipment and technique development have been rapidly transferred to the geothermal industry.

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*A MODEL OF THE SERRAZZANO ZONE**

O. Weres

LITHOLOGY

For hydrogeological purposes, the rocks of the Larderello Basin may be divided into three main complexes.[1]

The first is a weakly metamorphic basement complex of quartzites, phyllites, and schists. Although deep exploratory drilling has found occasional fractures and isolated pockets of permeable rock, it is believed that the basement complex is largely impermeable and contributes little to steam production.

The second is a so-called "evaporite" complex of anhydrite, limestones, dolostones, and radiolarites. These rocks are absent in some areas and up to a kilometer thick in others. The limestones and dolostones are known to be highly porous and permeable. The lower-lying anhydrite is believed to be highly porous and permeable where it has been tectonically sheared and brecciated. Because a major regional thrust fault passes through this complex, the tectonically sheared and brecciated zones are believed to be extensive. Overall, this complex is believed to be the main reservoir of liquid water and source of steam in the geothermal system.

The last complex is a largely sedimentary caprock sequence consisting of unmetamorphosed and weakly metamorphosed shales, marls, feldspathic sandstones, and ophiolitic rocks. Although there are significant volumes of permeable and porous limestones and sandstones in this complex, the preponderance of argillaceous rock types make it effectively impermeable as a whole. It serves as a caprock for the geothermal system.

STRUCTURE

Most wells in the Larderello Basin produce from an interval at or near the bottom margin of the caprock. Where the evaporites are absent, the producing interval is the thrust fault zone at the contact of basement and caprock. This fault zone is not the ultimate source of steam, but only a conduit, which conducts the steam from permeable complex rocks to the wellbores.

The elevation of first commercial steam throughout the Basin is shown in Figure 1. It is apparent that the Castelnuovo-Larderello, Serrazzano, Lago, and Lagoni Rossi productive areas are centered near distinct highs in the reservoir top.[2] (These areas account for 9/10 of the Basin's steam production.) At Castelnuovo-Larderello and Serrazzano the permeable comlex rocks are thin or absent and the highs are simply highs in the basement.

RESERVOIR STATICS AND DYNAMICS

There is a clear analogy to the well-known structural trap reservoirs of petroleum geology. Steam can be trapped under an anticlinal caprock as petroleum can.

There appears to be reasonably continuous permeabiity and flow at the reservoir top throughout the Basin. Isotopically demonstrated flow of water from surrounding aquifers into the reservoir[3] indicates hydraulic continuity with them as well. This suggests that prior to exploitation there must have been hydrostatic equilibrium between reservoir and aquifers. The (simplified) condition for such equilibrium is that

$$h_{aq} - h_{res} = 10 = 10 \times [P_{sat}(T_{res}) - 1]$$

where h_{aq} is the isopiestic level of the surrounding aquifers (in meters), h_{res} is the elevation of the steam-water interface under the trap, and $P_{sat}(T_{res})$ is the steam saturation pressure at reservoir temperature. Analysis of water level and temperature survey data from the few "wet" wells in the Serrazzano zone should provide a good test for this equation.

A detailed analysis of various published data has led to an estimate of 275°C for the initial reservoir temperature. Because h_{aq} averages about 100 m around the periphery of the Basin, an initial h_{res} of about -500 m is indicated.[4] This

* Presented at the Third Geothermal Reservoir Workshop at Stanford University, December 14-16, 1977.

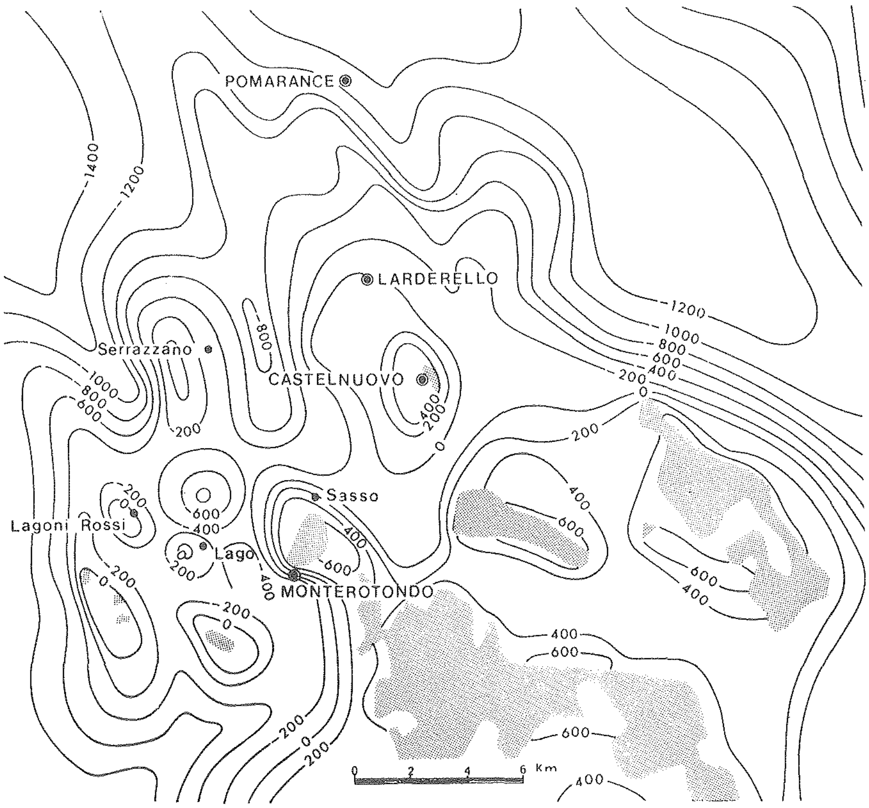

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Figure 1. Elevation of reservoir top throughout Larderello Basin in meters. Shaded areas indicate "evaporite" outcrops. (From Reference 2.)

is deep enough to allow for fair-sized initial steam zones in the major areas.

Early wells never reached 500 m subsea and never encountered water. The fact that most modern deep wells have also not encountered water is probably due to a lowering of the water table by steam production.

Hydrogen and oxygen isotope studies[3] show clear evidence of massive incursions of recently meteoric groundwaters from the southeast of Castelnuovo and Sasso. Smaller incursions are suggested from the southwest between Lagoni Rossi and Lago, and from the west at Serrazzano.

It is likely that the incursion of surrounding cooler groundwaters is due to the lowering of reservoir pressure caused by steam production. A hydrological balance calculated for the entire basin suggests that the rate of recharge is about one-third that of steam production.[5]

TOWARD A NUMERICAL MODEL OF THE SERRAZZANO ZONE

LBL's part in the DOE/ENEL cooperative program is to numerically model the reservoir dynamics of the Serrazzano and Castelnuovo zones. The author is presently engaged in developing a geologically accurate computer-generated mesh for use in modeling Serrazzano.

Figure 2 shows a recent version of this mesh. The input data for the mesh generator are essentially a set of digitized geological cross-sections. The two cross-sectionsd labeled in Figure 2 are plotted in Figure 3. The three lithological layers distinguished in the cross-sections are the three complexes defined and discussed above. Where there is a significant thickness of "the evaporites," the mesh elements all lie completely within this complex. Where the basement and caprock are in direct contact, the mesh elements are taken to lie along the contact surface and to be about 120 m thick. This thickness was chosen because it is about twice the root mean square distance for heat diffusion through rock over 25 years. (This roughly corresponds to the history of full-scale steam production at Serrazzano.) The underlying physical model is that of steam flowing through a thin fault zone and extracting heat from the surrounding impermeable rock by conduction.

The points plotted within the evaporite stratum and at the caprock-basement contact correspond to the individual elements of the mesh. The points within the basement or caprock and not on the contact do not correspond to mesh elements. Their function is to define the bounding planes of the adjacent mesh elements. In all cases, the bounding and interface planes are the plane bisectors of the line segments between the

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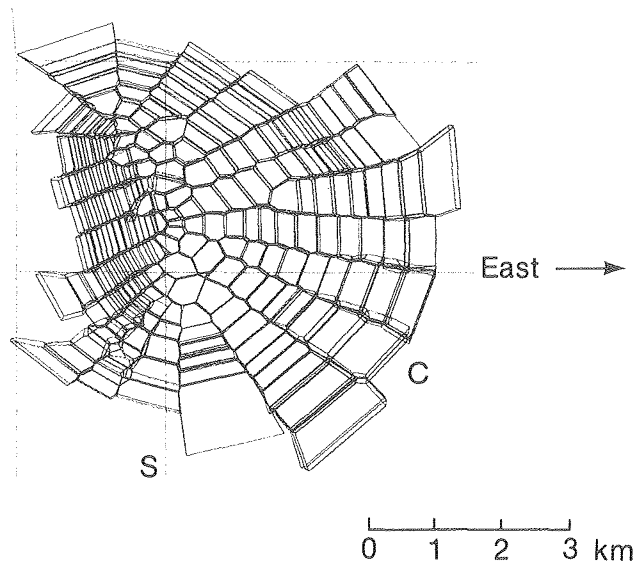

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Figure 2. A computer-generated mesh for modeling the Serrazzano zone reservoir.

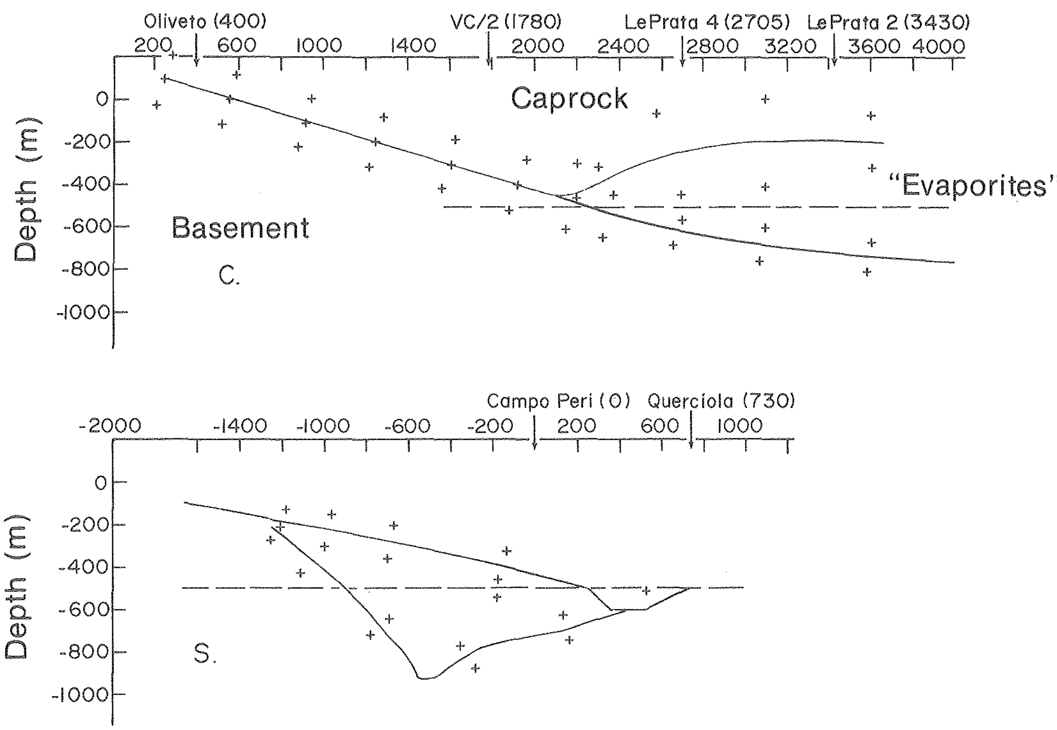

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Figure 3. Typical geological cross-sections of Serrazzano zone. The points are input for the mesh generator code.

corresponding pairs of points. This prescription for choosing interface planes is believed to be optimal for our purposes. The only input data required are the coordinates of the various points. The mesh shown has 227 elements and 448 bounding points. The calculation found 2404 boundary and interface planes between them.

WATER RESERVES AND BOUNDARY CONDITIONS

The mesh in Figure 2 is geologically accurate in its depiction of the reservoir, and the volume and elevation of each element is known. This allows us to estimate initial heat and water reserves within the region modeled.

Figure 4 shows only those elements containing about one-half or more "evaporitic" rock. The total volume of these elements is about 4.2 km^3. Of this, about 3.1 km^3 are below about 450 to 500 m and were probably initially water saturated. How much water this represents depends on the average porosity, which is unknown. If we make a moderately optimistic estimate of 10% porosity, this is 0.31 km^3. Assuming an initial water temperature of 275°C the estimated initial mass would be about 2.3×10^8 metric tons. This amount of steam would suffice to run the 32-MW Serrazzano power plant for about 100 years. The magnitude is completely consistent with cumulative steam production of about 0.9×10^8 metric tons to date.

Clearly, the extent of mass flow in and out of the region studied will also affect the validity of such estimates. In this regard, it appears that the Serrazzano zone is the most isolated subarea within the Larderello Basin. (This is one reason why Serrazzano was chosen for study. The other is that relatively complete historical production data are available.) However, as is evident from the concentration of the "evaporites" at the very edges of the mesh, Serrazzano cannot be perfectly isolated. The very thick evaporite stratum in the southeast corner of the mesh (also see Section C) is continuous with the diapiric evaporite outcrop between Monterotondo and Sasso. This is known to be a major recharge area.[3] Although the recharge water does not appear to have reached the Serrazzano zone yet, it is possible that it has already displaced significant volumes of "old" water toward Serrazzano. There may also be some influx of water and steam from west-southwest where the mesh is truncated due to lack of stratigraphic data. The large volume of evaporites in the south-southwest octant is about midway between Serrazzano on one side and Lagoni Rossi and Lago on the other. It is very likely that some of the steam generated here flows south toward the latter two zones.

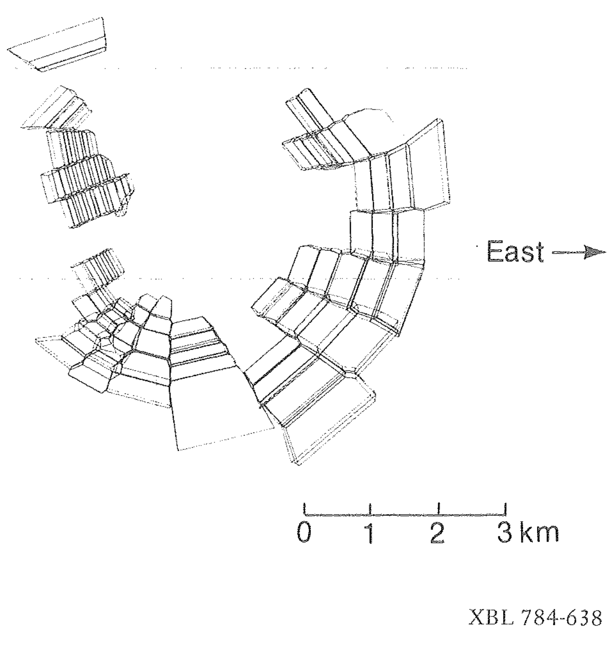

Figure 4. Computer-generated mesh for modeling the Serrazzano zone reservoir showing "evaporite" mesh elements only.

HEAT RESERVES

We will assume a volumetric heat capacity of 2,460 $kJ/m^3 \cdot {}^\circ C$ for the reservoir rock and an initial temperature of 275°C. A reasonable estimate for ultimate abandonment pressure is 8 bar, and this corresponds to an abandonment temperature of 170°C. We again take $\phi = 0.1$ for the "evaporites" and $\phi \approx 0$ for the other rock types.

This leads us to estimate the total quantity of useful heat within just the "evaporite" elements of the mesh to be about 9.8×10^{14} kJ. This quantity of heat is enough to convert 3.6×10^8 metric tons of water initially at 25°C to steam of 2,800 kJ/kg enthalpy. Water initally at 275°C would require less heat. If we assume an initial "preheated" water supply of 2.3×10^8 metric tons, we find that an equal volume of cold recharge water is needed to cool the evaporites down to 170°C. Another 2.0×10^8 metric tons would be required to cool the nonevaporite portions of the mesh down to 170°C, for a grand total steam production of 6.6×10^8 tons. This is enough for 9,400 MW-years of electrical generation.

It seems clear that water reserves will prove to be the limiting factor at Serrazzano. A long-term program of water injection appears to be called for if anything like the above figure is to be reached.

ACKNOWLEDGMENTS

I would like to thank Ron Schroeder and Romano Celati for stimulating discussions and correspondence, which contributed much to the development and refinement of this model. In particular, Ron Schroeder directed my attention to the "trap" nature of the Serrazzano structure. I wish to thank the ENEL geothermal staff as a whole for kindly allowing us access to their voluminous unpublished data which made this work possible.

Mr. Chris Weaver generated the excellent graphics which make my mesh output comprehensible. Ms. Chris Doughty assisted me with the tedious work of digitizing the geological input data.

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*RESERVOIR SIMULATION OF THE SERRAZZANO AND CASTELNUOVO ZONES AT LARDERELLO, ITALY**

R. C. Schroeder, O. Weres, and P. A. Witherspoon

THE SERRAZZANO GEOTHERMAL FIELD

The geology of Serrazzano field is characterized by an anticlinal-type structure made up of Triassic-Paleozoic formations; the upper part of these formations is represented by quartzites and quartzose conglomerates and the lower part by phyllites.

These formations are overlain, on the margins of the structure, by a thin layer of Triassic dolomites and anhydrites; above the previous formations there is a complex of flysch facies and marly clay terrains that form an impermeable cover. The Triassic-Paleozoic terrains form the potential reservoir.

Fracturation has developed mainly in the upper part of the structure, as a consequence of the tectonic movements accompanying the emplacement of the flysch and the folding phenomena. The northern margin of the Serrazzano field is made up of low-temperature formations that also form the boundaries of the explored area. The other margins of the field are characterized by very low permeability compared with that in the productive area.

One problem in modeling is to define the initial state of a given system. In the case of Serrazzano, there is no direct solution to this problem because very few measurements have been made and drilling has not followed any set pattern. There were originally some natural manifestations in the uppermost part of the structure and for many years the search for steam was concentrated exclusively in these zones. Knowledge of the entire field was therefore acquired gradually over a rather long period, which is not a unique situation in reservoir development. During the nineteenth century there was a small production from a few shallow wells. In 1905 there were 52 boreholes producing fluids, sometimes superheated steam, at a pressure slightly above atmospheric. Total flow rate at that time is unknown, but we do know that in 1922 flow rate was about 40 tons/hr.

These boreholes were so shallow that they probably managed to produce steam without modifying the thermodynamic conditions of the reservoir. The reservoir was then probably in a stationary state, so that the total steam flow rate from these boreholes gives us a rough estimate of the quantity of steam produced in the reservoir per unit of time.

The first deep wells were drilled between 1930 and 1940 in the exploitation area. At their maximum depth of 200 m, these wells began production at the contact between the impermeable complex terrains and those of the underlying formations. We have no data for defining the shut-in pressure of these wells; although some production tests were carried out at varying pressures in some wells, they do not seem sufficiently stable for an eventual evaluation of shut-in pressure. Wells were first shut in between 1954 and 1955; these were the Canteo and the Cioccaia wells, located very near the production area. The pressure in these wells was about 12 kg/cm^2. During this same period, drilling began again after an interval caused by the outbreak of World War II.

At present the field produces about 300 tons/hr of fluid, comprising 96.5% superheated steam and 3.5% different gases. Average production pressure is about 5 kg/cm^2 abs. Flow rate in the more productive wells has decreased very rapidly; in the less productive wells flow rate has decreased more slowly. Measurements taken in 1941 show that wells that are now producing 60 tons/hr were then producing 220 tons/hr of steam.

The area of the field that was the first to be exploited now produces 16% of the field's total production. The fluid from this area is 96.5%

* This is a condensation of two papers presented in collaboration with the following Italian coauthors: R. Celati, R. Marconcini, G. Neri, and C. Ruffilli at the Larderello Geothermal Workshop, September 1977.

steam in average conditions of 190°C temperature and 5 kg/cm^2 abs. pressure. The other productive wells produce steam at higher average temperatures. One characteristic common to the producing wells is that the steam enters through fractures, usually those near the contact between the cover terrains and the potential reservoir.

In view of the objectives of our project, we calculated all the flow rate, pressure, and temperature measurements of the productive and shut-in wells at well bottom. These calculations took into account the pressure and temperature loss due to production of steam from the boreholes. The method we used was originally proposed by Bozza[1] and later extended by Rumi.[2] Wellbore heat conduction was calculated using Ramey's equations.[3] Generally, there is very little difference between pressure and temperature values measured at wellhead and those calculated at well bottom. This is explained by the large diameters of the pipelines used in the wells, and by the relatively low flow rates, so that the velocity of the steam flow is at least one order of magnitude lower than the fluid sonic velocity.

The water table hypothesized by many researchers has never been located. Recently, while drilling well Sperimentale 1 in the middle of the main productive area, a fracture was encountered at a depth of 1,930 m. This fracture may be in communication with an aquifer at temperatures of 280-290°C, and pressure of about 75 kg/cm^2 abs. The water recharge areas have not yet been adequately defined for the Serrazzano field, although one such area may exist on the northwest side where there is a hydraulic gradient towards the field.

Reservoir Simulation

Two simulation grids were constructed to approximate the geology of Serrazzano. Both are three-dimensional, and both have large numbers of elements. The first grid, as shown by the cross-sectional representations in Figures 1 and 2, includes only the rock mass along which the fracture system is believed to exist[4] and the porous anhydrite-dolomite formation between the caprock and the basement complex. A second grid as shown in Figures 3 to 9 was constructed in a more crude manner to attempt to study the hypothesis of water

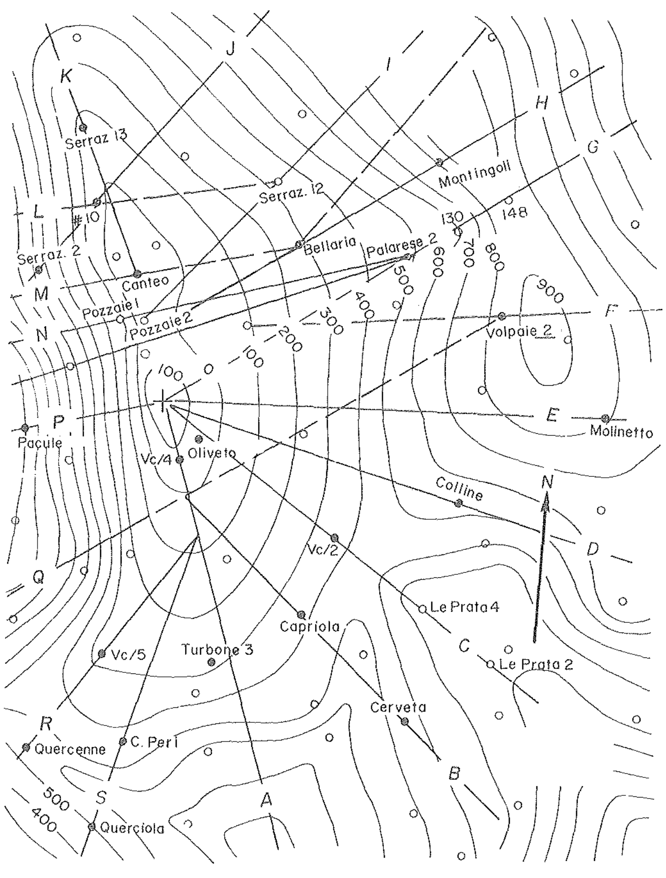


Figure 1. Areal view of the Serrazzano zone with solid lines labeled A to S, indicating the cross sections.

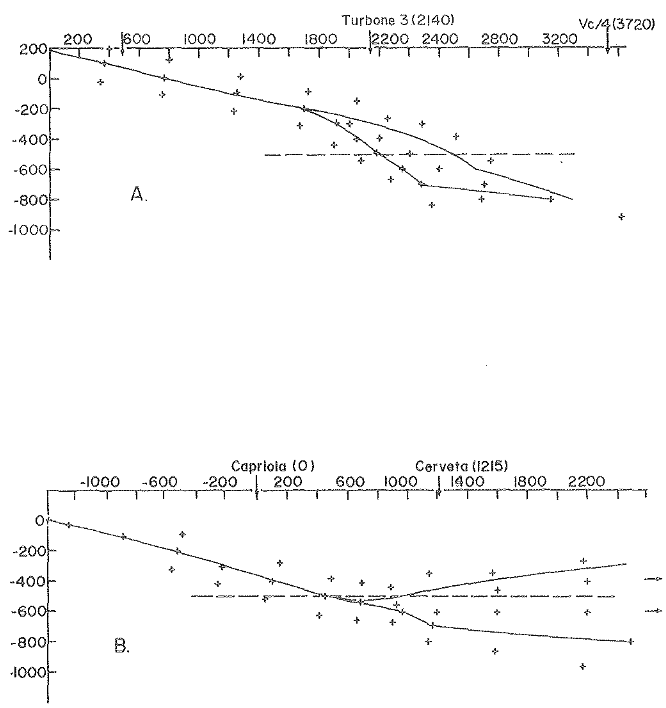
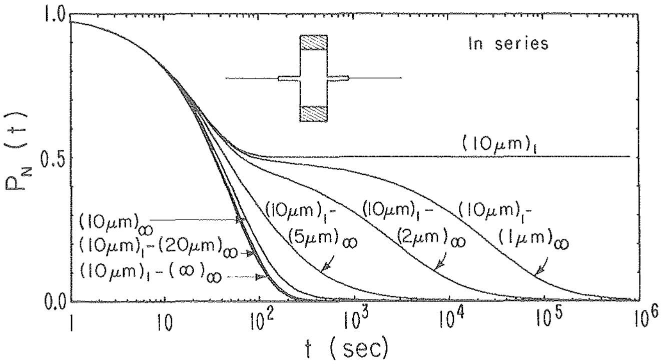


Figure 2. Cross sections A and B from Figure 1, showing the simulation element locations (+), and the upper and lower boundaries of the reservoir (fracture where only one line is shown).



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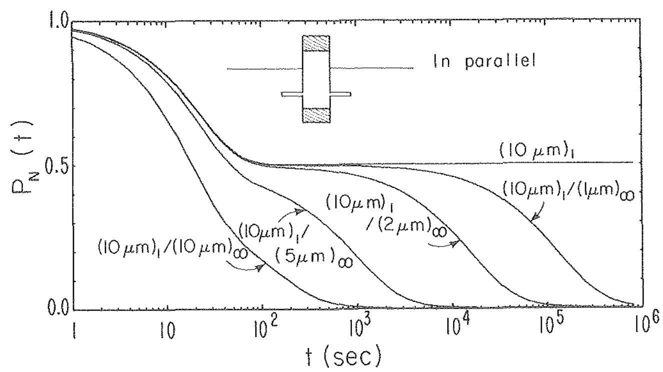

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Figure 4. Normalized pressure decay at a wellbore intersected by a 10-μm fracture with finite volume $V_F/V_w = 1$ (a) in series, or (b) in parallel, with an aperture 2b fracture with infinite volume.

in the required time due to finite fracture boundaries are also shown. The set of curves for the infinite fracture can be fitted to straight lines which can be used for a quick estimation of the aperture in the field. Over a short time period, a general complex fracture system intersecting a wellbore will behave like a single infinite fracture. Figure 3 or the straight line formula can be used as the starting point for analyzing the pulse packer test. The explicit formula of the straight lines, the scaling to different wellbore dimensions and fluid properties, the possible errors in this simple analysis, together with the use of type curve fitting for deducing the fracture properties are discussed in Reference 1.

Over short times the pressure decay is mainly determined by the near-wellbore flow and is insensitive to the fracture properties away from the wellbore. Over long times the fracture geometry may profoundly affect the pressure changes. This is obvious for the single closed finite fracture shown in Figure 2(a) with nonzero asymptotic values due to finite volume effect. To demonstrate the effect of connectivity of multifractures on transient flow, the pressure declines due to 10-μm finite fractures with $V_F/V_w = 1$ in series or parallel to an infinite fracture ($V_F/V_w = \infty$) are plotted in Figure 4 [see the sketches in Figure 4(a) and 4(b) for the geometrical arrangements]. The in-series fractures interact directly while the in-parallel fractures communicate through the wellbore only. From the comparisons in Figure 4, it is clear that the interaction between the two fractures is significant over longer time periods. These results demonstrate the potential usage of the long-time data to deduce the fracture network properties. In Reference 1, the use of interference tests for studying the fracture properties between two wellbores are also discussed.

PLANNED ACTIVITIES FOR 1978

1. Study the effect of transient flow in intersecting fracture planes. Superposition of simple solutions or numerical modeling will be used in the calculations.

2. Develop further the analysis of interference tests. Simultaneous pulsing from different wellbores, or periodic pulsing, are interesting generalizations.

3. Study the effect of pressure-induced deformation of the fractures. This nonlinear effect is important if the pressure pulse is large enough to affect substantially the existing stress state of the fracture.

4. Assist the development of the well testing programs in the field and in the laboratory.

REFERENCE

1. Wang, J.S.Y., Narasimhan, T.N., Tsang, C.F., and Witherspoon, P.A. Transient Flow in Tight Fractures. To be published in the Proceedings of the Invitational Well Testing Symposium at Berkeley, California, October 19-21, 1977. Also, Lawrence Berkeley Laboratory report, LBL-7026.

5. APPLIED GEOSCIENCES

The applied geosciences program includes projects in uranium resource assessment, enhanced oil recovery, and interpretation of data obtained with airborne remote-sensing devices. The uranium project investigates the resource potential in alkaline, peralkaline, and carbonatitic rocks. These rock types, whose resource potential has been recognized in other countries, are present in the United States and may contain substantial recoverable quantities of uranium. An active project investigates the enhanced recovery of oil from reservoirs by use of flooding with alkaline fluids. Concurrently, projects are being developed to investigate other aspects of enhanced oil recovery. Interpretation of airborne radiometric and multispectral data from flights over reactor sites and other energy-related projects is the subject of an on-going program. By encompassing projects not directly associated with fundamental geosciences, geothermal energy, or nuclear waste storage, the Division endeavors to broaden its scope of interest. In 1978 the Division will continue to explore new avenues in applied geosciences.

URANIUM IN ALKALINE IGNEOUS ROCKS

H. A. Wollenberg, M. Murphy, B. Strisower, H. Bowman, S. Flexser, and I. Carmichael

In conjunction with the Bendix Field Engineering Corporation and the Grand Junction Office of DOE, LBL is conducting a project to identify the uranium resource potential of alkaline and peralkaline plutons, and carbonatitic rocks of the United States. In this project, based mainly on a literature search, known uraniferous alkaline rock areas outside the United States are characterized and compared with alkaline rock areas in the United States, leading to a choice of candidate sites for further examination. Criteria considered in the characterization include lithology of the alkaline occurrences and surrounding country rock, and their tectonic setting and geochemistry, with emphasis on radioelements (U and Th) and companion trace elements (Zr, Nb, Be, F and rare earths).

The principal foreign alkaline uranium occurrences, Poços de Caldas, Brazil (with reserves of 10,000-15,000 tons of uranium oxide), and Ilímaussaq, Greenland (where reserves in excess of 20,000 tons have been identified), were visited in 1977 and their attributes compared with those of U.S. occurrences of similar lithology and tectonic setting. Field visits, combined with the literature search, have identified type-occurrences in alkaline rocks against which U.S. occurrences are being compared. Samples of alkaline rocks in the University of California collection and specimens of mineralized rock from Poços de Caldas are being analyzed for their major and trace-element contents.

Four type-occurrences are summarized in Tables 1-4: the aforementioned Greenland and Brazilian occurrences, and those at Bokan Mountain, Alaska and the Ottawa Graben region of Canada.

An additional type-occurrence is the conjunction of hydrothermal mineralization with alkaline rocks, exemplified by sites in the Front Range of Colorado.

In early 1978 a number of occurrences in the U.S. having sufficient attributes to warrant field examination will be identified through the literature search. It has been proposed, then, that the second phase of the project will emphasize an examination of the sites, encompassing field radiometric surveys, sampling, and subsequent laboratory analyses. Results will disclose the validity of the choice of the sites and will provide information on which a more widespread assessment of the uranium resource potential of these rock types can be based.

Table 1. Ilímaussaq type-occurrence

- Strongly peralkaline layered intrusion
- Associated with layered ultrabasic rocks
- Intrudes Precambrian shield area
- Combination vein and disseminated mineralization
- Located in Precambrian rift zone
- High REE, Th, Nb, Zr, and Be affinity
- Uranium minerals - steenstrupine, thorite, pigmentary material
- Ore rocks - lujavrite, analcime/albite veins

Table 2. Poços de Caldas type-occurrence

- Moderately to strongly peralkaline shallow intrusion and breccia pipes
- Associated with a belt of peralkaline and carbonatite intrusions
- Intrudes Precambrian shield
- Vein type mineralization, hydrothermal alteration, and lateritic weathering
- Located at regional fault intersection
- High Zr, Mo, Th, and F affinity
- Uranium minerals - coffinite, uranothorite, flourine, and molybdenum minerals, secondary pitchblende
- Ore rocks - hydrothermally altered tinguaite breccia

Table 3. Bokan Mountain type-occurrence

- Peralkaline aegirine/riebeckite granite
- Associated with less alkaline granites, faylite granites
- Intrudes Precambrian to Paleozoic terrain
- Deuteric alteration, pegmatitic and disseminated mineralization
- Post orogenic emplacement
- High Th, Fe^{2+}, Mg, Pb affinity
- Uranium mineral - zircon, coffinite, uranothorite, and pigmentary material
- Ore rocks - adularia/albite zones, alkaline pegmatites

Table 4. Ottawa Graben type-occurrence

- Alkaline carbonatite ring dykes and plugs
- Associated with nepheline pyroxenite, nepheline syenite, and fenite
- Intrudes Precambrian shield
- Metasomatic mineralization, disseminated and/or segregated
- Active rift zones in some cases
- High Nb, Ree, Th, Fe^{2+} affinity
- Uranium minerals - betafite, uranian pyrochlore, pigmentary material
- Ore rocks - biotite carbonatite, apatite rock, fenite

INTERPRETATION OF AIRBORNE REMOTE-SENSING DATA

H. A. Wollenberg and D. di Somma

Geologic guidance was furnished by LBL for DOE-sponsored flights by E.G.&G. Inc., Las Vegas Operations, over underground combustion experiments at Hanna, Wyoming (coal gasification), Rock Springs, Wyoming (oil shale), and Vernal, Utah (tar sands). The imagery analyzed consisted of high resolution aerial photography and thermal-infrared scans of the sites. The missions were conducted to aid DOE's Laramie Research Center in assessing the environmental baseline status of the sites prior to development of these resources by in situ methods. Flights were made over areas of known surface subsidence from underground mining and over locations of mine fires, to see if surficial effects could be detected by aerial multi-spectral reconnaissance. Data tapes from recent flights of a new multi-spectral scanner are presently being analyzed by computer at E.G.&G. Resulting imagery will be interpreted to discern geologic, hydrologic, and vegetation patterns.

Results of airborne radiometric surveys by E.G.&G. over regions surrounding two reactor sites in Florida were analyzed, and their geologic settings compared with the observed gamma-ray field. Near the site in western Florida, sharp positive gamma anomalies coincided, as expected, with open-pit mines of phosphate rock in the Alachua Formation. The phosphate is naturally enriched in uranium and its daughter elements. In the site region in eastern Florida, moderately high radioactivity is associated with an area of orchards, indicating the use of phosphate and/or potash fertilizers.

To aid in geologic evaluation of aero-radiometric data, the Geodose Project, a literature-based characterization of rock types by their radioelement (U, Th, and K) contents, radiogenic heat production, and gamma-ray exposure rates, has been conducted. The computer program, DOSECAL, has been used to calculate heat production and exposure rates from radioelement data, to plot histograms, and express their statistical significance. To date, nearly 2400 entries have been processed, permitting characterization of 16 rock types.

ENHANCED RECOVERY WITH MOBILITY AND REACTIVE TENSION AGENTS

C. J. Radke and W. H. Somerton

INTRODUCTION

California crude oils, among others, contain significant amounts of natural acids which upon neutralization with bases can produce in situ surfactant salts. Thus the injection of alkaline water has long been thought attractive as a means for enhancing the generally poor oil recovery from California reservoirs. Alkaline water-flooding has a decided economic advantage over flooding with commercial surfactants and/or polymers and hence further field testing has been recently initiated under Department of Energy auspices (i.e., at oil fields being produced by THUMS, Long Beach Calif.; and Aminoil, Huntington Beach, Calif.). Unfortunately, published studies do not give a clear picture as to how to design an alkaline flood for effective oil recovery.

The objectives of the present study are (1) to establish the conditions requisite for tertiary-mode displacement of acidic oils with high pH agents, and (2) to elucidate the dominant recovery mechanisms and hence permit development of an improved alkaline flooding package. The overall project maintains close liaison with the current field work and includes studies of displacement of fluids from core samples from oil fields and synthetic systems, interfacial tensions, emulsion flow in porous media and, as of this fall, adsorption loss of alkaline agents. Each of these subprograms is summarized below; more detailed exposition of the work completed up to August 1 is available in Ref. 1.

CORE DISPLACEMENTS WITH OIL FIELD SYSTEMS

An apparatus for conducting displacement tests on actual oil field cores under anticipated field operating conditions was constructed and tested with typical cores and test fluids. A series of tests was then run on cores from the Ranger zone of the Wilmington oil field using Ranger zone crude oil, simulated formation brine, and alkaline flooding fluids of concentrations to be used by THUMS in planned field tests. No oil was recovered from the rubber sleeve core samples during either water flooding or chemical flooding of the cores. An excessive loss of chemicals by adsorption on mineral grain surfaces was noted. After completion of tests on the native cores, they were extracted in situ and resaturated with formation brine and crude oil. The cores were water-flooded to reach a water-oil ratio of 5:1 and then flooded with caustic (0.1 weight %) to residual oil saturation. There were three significant findings from these latter tests: (1) chemical flooding was shown to recover about 35% of the oil remaining after water-flooding; (2) oil recovery was extremely sensitive to flooding rates, lower recovery being obtained at the low flooding rates typical of field operations; and (3) loss of caustic to the core was high and perhaps excessive for successful caustic flooding of these high clay content reservoir sands. The first finding is especially significant because no attempt was made to optimize the chemistry of the flooding solution. Finding (3) was unexpected and has evoked a study on caustic loss in the reservoir sand.

During the coming year, oil field core flooding tests will be continued to confirm the above noted behavior on a wider variety of cores from the Ranger zone. Rate sensitivity tests will be made in an effort to properly account for this variable on recovery results. Efforts will be made to optimize the concentrations of chemicals and the application techniques to achieve the greatest recovery of residual oil.

SYNTHETIC SYSTEMS

To enumerate recovery mechanisms, displacement studies are conducted on oleic-acid-doped mineral oils in quartz sand-packs with various alkaline agents and salts. The apparatus has been described previously.[1] Standard tertiary floods are performed while pH and pressure drop are continuously monitored. Also, the fluids are tested for spontaneous emulsification, shear emulsion, emulsion type, and emulsion stability. Results of the 11 consistent floods performed to date indicate that: (1) stable, high-tension oil-in-water emulsions cause plugging through droplet entrapment in pore constrictions; (2) in five floods tertiary recovery efficiencies of 50% were attained. In those floods that do recovery tertiary oil, the common features are oil production in a narrow bank with concomitant large increases in water permeability, the formation external to the flood of stable water-in-oil emulsions, and high dynamic interfacial tensions.

Studies, including micromodel observations, are continuing to ascertain the recovery mechanisms. Changes in wettability will be established through contact angle measurements. In addition, the effects of acid chemical nature, oil viscosity, absolute permeability, and flooding rate will be investigated.

INTERFACIAL TENSIONS

Because of the possible occurrence of the capillary displacement mechanism, the conditions under which saponified acids cause ultralow tensions are pursued. In the in situ production of surfactants during alkaline flooding, a range of concentrations is possible; hence, there is a question as to which concentration or tension actually characterizes the displacement process. To gain insight into the possible concentration profiles, an ideal equilibrium chromatographic model has been developed. The neutralization equilibria are represented by:

$$HA_{oil} \overset{K_D}{\rightleftarrows} HA_{water}$$

$$HA_{water} \overset{K_A}{\rightleftarrows} H^+ + A^-$$

$$H_2O \overset{K_W}{\rightleftarrows} H^+ + OH^-$$

where A^- denotes the saponified surfactant species (e.g., oleate ion). If the oil phase is stationary, the equilibria are instantaneous and there is negligible adsorption or dispersion; unsteady species continuity balances on the alkaline agent cation and on the surfactant ion (in all forms) completely determine all species concentration profiles. The solution demands two shock fronts. In the first front, all injected and produced chemicals establish equilibrium with the original acid oil phase. In the second front, all the acid has been extracted from the oil phase and only the injected alkaline agent moves. Thus the two bounding tensions, which appear to characterize the flooding process, are the dynamic tension when the base first contacts an oil globule and the tension when the base has estabished equilibrium with an infinite amount of the original acid oil. The present chromatographic treatment also provides a starting point for a more general analysis of alkaline flooding by relaxing some or all of the underlying assumptions.

Dynamic oil-water interfacial tensions for aqueous bases contacting acid oils in a spinning drop apparatus have dramatic minima.[1] These evolution minima appear only when mass transfer occurs from the oil to the water phase. Thus a five-step sequence was previously enunciated:

transport of the acid to the oil-water interface, adsorption of the acid, reaction of the acid to produce the surfactant, desorption of the surfactant, and transport into the bulk aqueous phase.[1] A quantitative model reflecting this sequence has now been formulated to portray the dynamic tensions in the spinning drop instrument. The model assumes well-mixed finite phases, a fast neutralization reaction, sorption barriers characterized by first-order chemical reactions, and quasi-static equilibrium for the drop shape and tension-adsorption relationship. Material balances on the surfactant species in the oil phase, in the water phase, and at the oil-water interface then predict the dynamic tension. Because the droplet area and surfactant adsorption are coupled, solution of the material-balance ordinary differential equations is difficult. However, even with the zeroth approximation of a constant interfacial area, a tension minimum is obtained.

EMULSION FLOW

Because of the possibility of mobility control with in situ formed emulsions, flow behavior is studied for stable oil-in-water emulsions of drop sizes greater than pore-entry diameters through consolidated and unconsolidated porous media. Experiments performed previously indicate large flow-rate-dependent permeability reductions even for dilute low-viscosity emulsified oils in high permeability media.[1] A quantitative flow model to predict these effects was also described previously.[1] The model is based on filtration theory but because droplets may "squeeze" through some larger pores a re-entrainment rate, which depends on local pressure drop, must be included in the theory. Thus pressure profiles and drop retention profiles are coupled, and solution of a highly non-linear partial integrodifferential equation is required.

Progress since August includes the following. First, incorporation of a periodic constricted tube porous-medium model to quantify the filter coefficient, the fraction of drops diverted, and the local permeability. Thus, once the pore size distribution, initial permeability and porosity, and drop size and interfacial tension are measured, all parameters are specified a priori. Second, a numerical procedure has been designed that reduces solution of the partial integrodifferential equation to simple numerical integrations.

ADSORPTION LOSS

Because alkaline-agent consumption by California reservoir rock was found to be unexpectedly large, a study on adsorption loss was recently started. Two precision, constant-rate pumps furnish solutions, differing in pH, through a selector valve to a thermostated adsorption column. Detection of outlet hydroxyl concentration is by continuous index of refraction and by collected solution pH. Adsorption isotherms are then constructed by rigorous frontal-analysis chromatography. Preliminary results reveal that isotherms that are convex for the outlet adsorption concentration fronts are much sharper than the outlet desorption concentration fronts.

REFERENCES

1. Radke, C.J. and Somerton, W.H. Enhanced Recovery with Mobility and Reactive Tension Agents. Third ERDA Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Methods, Tulsa, Vol. 1, pB-5, 1977.

ENHANCED OIL RECOVERY PROGRAM DEVELOPMENT

A. N. Graf, J. H. Howard, and P. A. Witherspoon

During the last quarter of fiscal year 1977 the potential for developing further research opportunities at LBL in enhanced oil recovery (EOR) was examined.

Major questions recognized during the course of this investigation are: What approach and level of activity should LBL undertake? and Which EOR method or methods should LBL concentrate on? Three non-exclusive approaches have been identified: 1. Comprehensive - Creation and coordination of a consortium which includes government, industry, national laboratories, and individuals conducting research and auxiliary functions at various levels for the purpose of supporting large-scale field tests of a particular EOR method. 2. Programmatic - Continuation of the current approach, which consists of small programs dealing with specific problems of various EOR methods, for example, use of surfactants in EOR. 3. Management - Manage pass-through government contract funding with discretionary funding for LBL programs. In the evaluations of EOR method or methods which deserve LBL's attention, two primary factors were considered: expected rate of growth of government funding, and competition. Based on these factors, the following priorities were established for EOR methods: first priority - steam drive and CO_2 miscible; second priority - micellar/polymer-improved water flooding and special targets; third priority - in situ combustion.

Investigations in several areas during fiscal year 1978 are anticipated in order to: assess LBL's resources; develop potential industrial/government/institutional alliances; conduct preliminary analysis of inactive California oil fields to determine applicable methods; consider EOR method(s) which might receive LBL's primary attention; and develop a plan for future EOR programs at LBL.

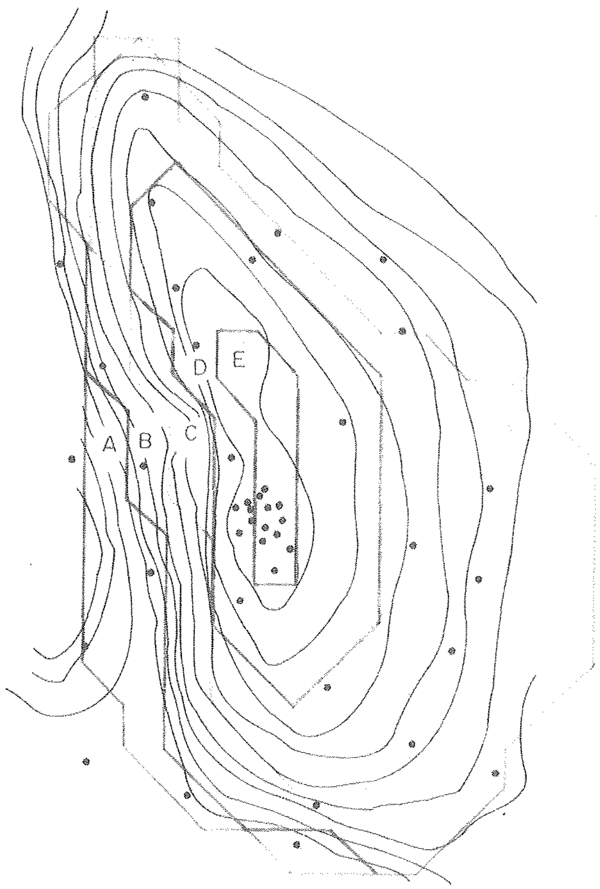

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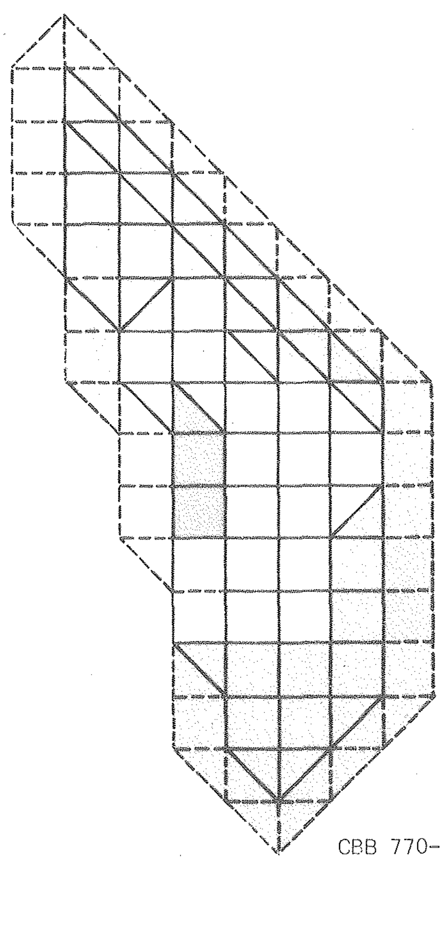
Figure 3. The shaded forms are the approximate kh distributions. The geometric outlines indicate the shapes of layers A, B, C, D and E, which were used in the SHAFT simulation.

dispersed throughout the region between the Argille Scagliose and the deep basement complex. This grid may also be important in studies of initial rock mass temperatures. However, the more accurate geological representation in the first grid (Figs. 1 and 2) will probably give the best results for fluid recharge studies.

The complete set of downhole production data including flow rate, pressure, and temperature values from 1930 to 1976 has been digitized and prepared for processing during the simulation. The SHAFT program will use the material parameters, initial condition, boundary conditions, and the transient record of flow rates and temperatures at the production wells as input data and will calculate the pressure, temperature, density and saturation at all spatial elements. Referring back to Figures 1 and 3, we see that the simulation is modeling a reservoir which is more than 5 km long and 1 km deep. To study the effect of water recharge from the surrounding areas, these large dimensions are necessary since the existing hydrological model has the recharge appearing at the periphery of the main production region.[5,6] The grid



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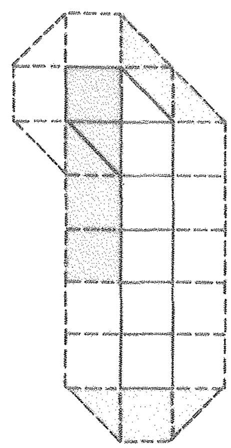

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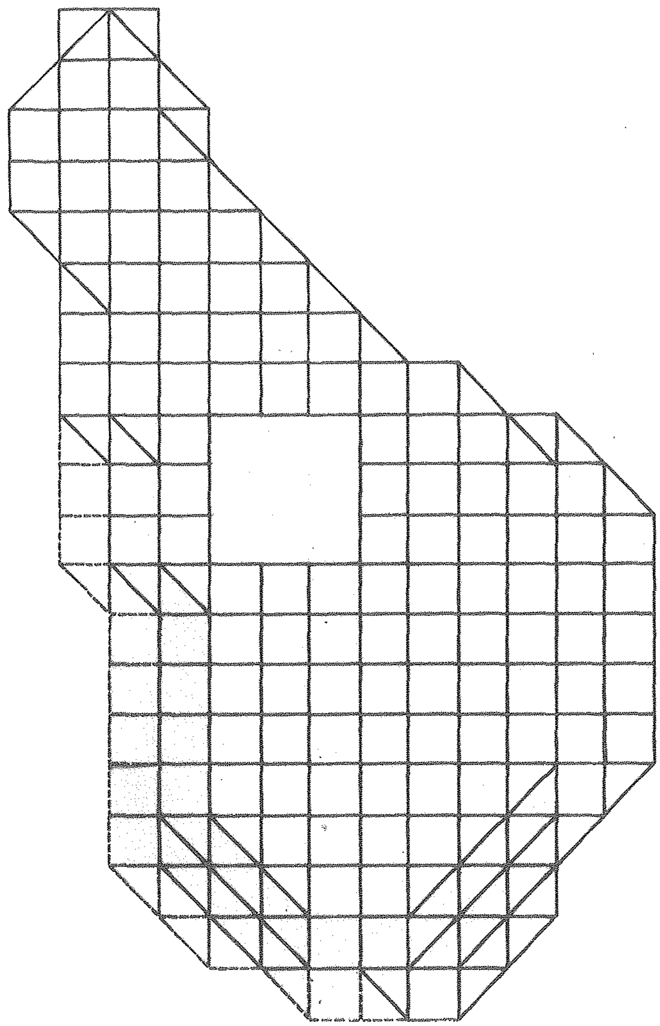
Figure 4. Left: Layer D, the second layer in the SHAFT simulation. Top elevation is -100m; the thickness of the layer is 200m. Right: Layer E, the first (top) layer in the SHAFT simulation. The solid lines denote parallelepideds; the dotted lines denote triangular-shaped elements.



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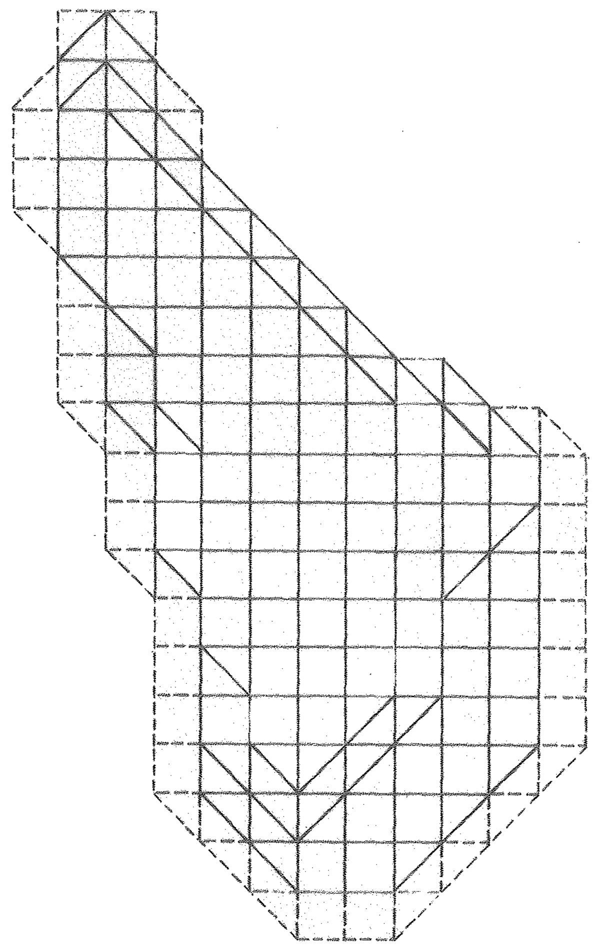

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Figure 5. Left: Layer B, the fourth layer in the SHAFT simulation. The top elevation is -650 m; the layer is 350 m thick. Right: Layer C, the third layer in the SHAFT simulation. The top elevation is -300 m; the layer is 350 m thick.

shown in Figure 3 covers a smaller area, but includes the interior volume. As a result of the need to include the "entire" reservoir in these two different representations, we were forced to use large numbers of elements. The number of elements in each grid exceeds 500. Although this does not cause any fundamental problems in our calculations, we are limited by the memory capacity of our computer. The codes have been modifed to use the entire small- and large-core memory of the CDC-7600 computer. This modification is currently being completed, and will enable us to use a large number of elements since the large-core memory of the CDC-7600 has a capacity greater than our future needs.

A report is currently being prepared which will describe a series of test calculations that have been carried out using the SHAFT program. These test problems were designed to verify the SHAFT program and to anticipate any problems that might arise during the full reservoir simulation.

Future Work

We will begin the Serrazzano calculations as soon as the program expansion into large-core memory is complete and the program has been tested with one or more of the test problems. The initial history match calculations will include the determination of the "best" parameters and boundary conditions. Following this initial phase of calculations, the future Serrazzano depletion will be calculated. The final calculations will include the effects of reinjection.

INJECTION EXPERIENCE IN ITALY

Water has been injected into several wells in Italian geothermal fields.[7] One example of long-term injection is the well Monterotondo 20 in the Monterotondo region of Larderello, where injection begain in June 1974 and continues today at the approximate rate of 40 m^3/hr. Another example is the well Carboli D in the Lago region of

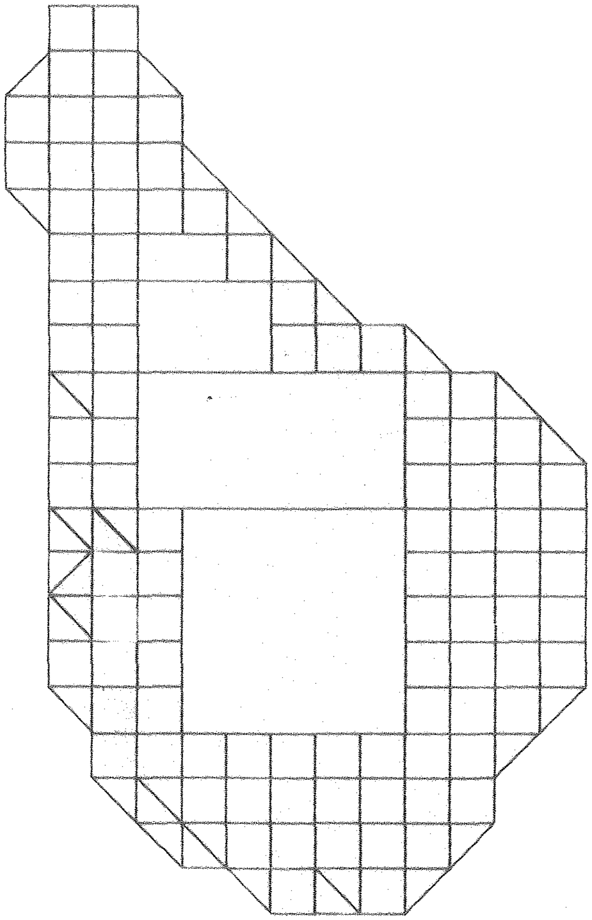

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Figure 6. Layer A, the lower layer of the "reservoir." The top of the layer is at -1000 m; the layer is 350 m thick.

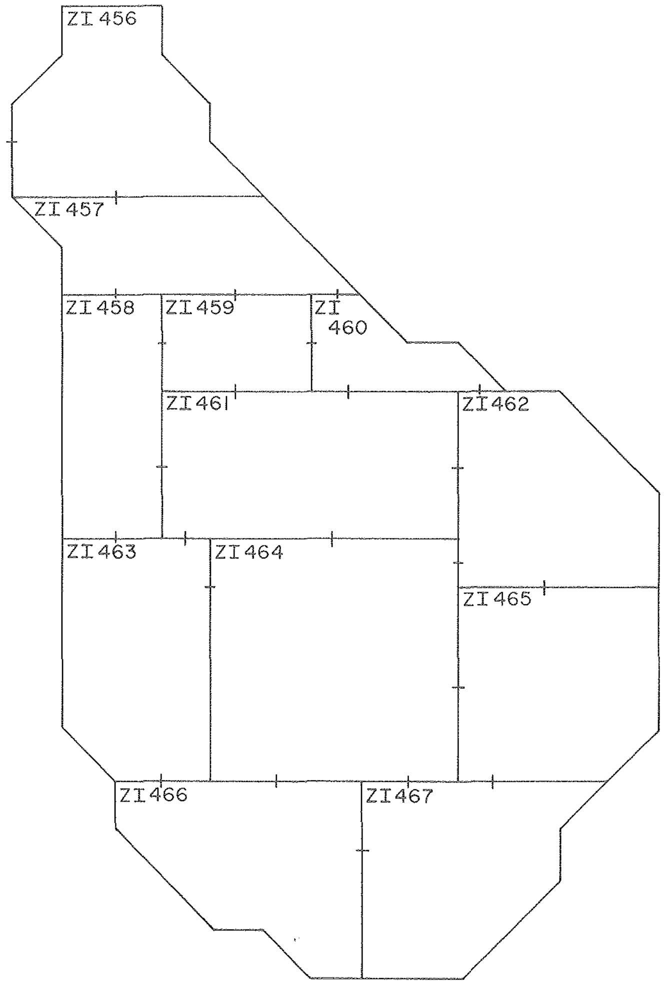

Figure 7. Layer Z, the deep formation below (?) the reservoir. The top elevation is -1350 m, and layer Z is 1000 m thick.

Larderello.[7] Injection began in this well in October 1974 and also continues today. However, these two wells are outside the main production regions in the respective fields, and the effects of the long-term injection in these two wells have not been observed in any steam-production wells.

CASTELNUOVO AND SPERIMENTALE 2

During the drilling of wells in vapor-dominated reservoirs in Italy, water has been used when a loss of circulation prevents the continued use of drilling mud. In several cases water has been injected into fracture zones during well drilling. Usually this injection occurs for a short period of time, but in the case of the experimental well, Sperimentale 2 (Sp2) in the Castelnuovo field, the injection continued for three months. The Castelnuovo field was exploited over a period of 35 years. The production wells range in depth from about 300 to 500 m. As a consequence of the production, the formation pressure in the upper part of the reservoir decreased below 4 ata. A few deeper wells (≈800 m) have shown shut-in pressure of between 6 and 10 ata in the last few years. Figure 10 shows the location of well Sp2. During the drilling (and injection of water) of Sp2, five surrounding steam producing wells were significantly perturbed. The injection measurements at Sp2 and the measured changes in the surrounding wells provide the best data for numerical simulation. The "reservoir" consists of two adjacent layers. The upper layer is a dense sandstone (Macigno) and the lower layer is made up of evaporitic anhydrites and magnesian limestone.

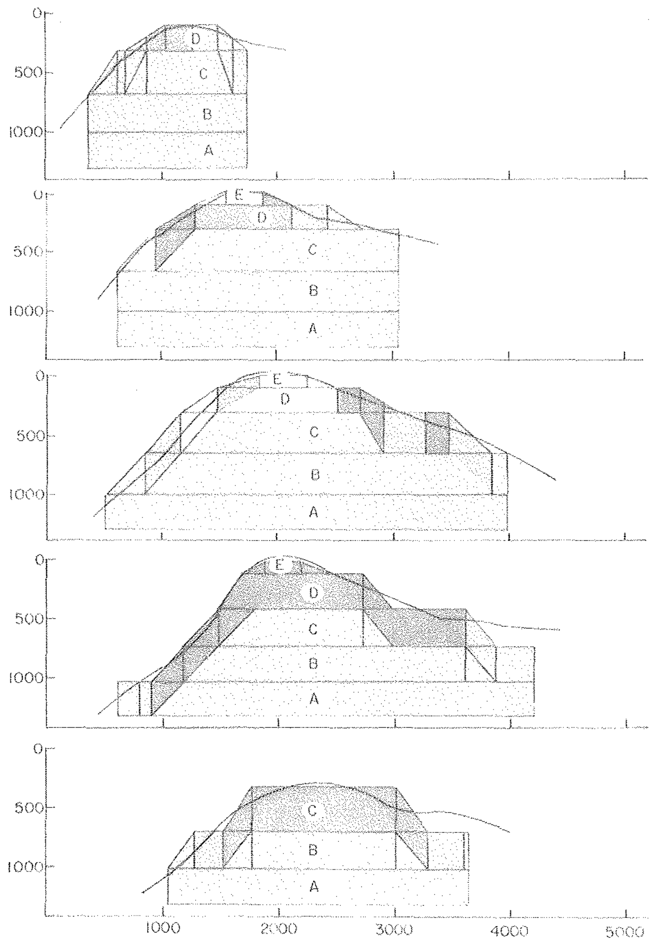

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Figure 8. Simulation layers shown to represent the reservoir in the SHAFT simulation. The heavy black curves are the approximate basement contours, and the geometric shaded areas are the discrete approximation.

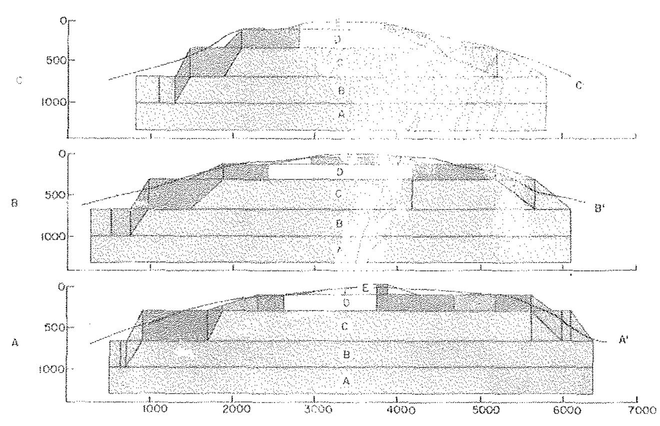

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Figure 9. Simulation layers chosen to represent the reservoir in the SHAFT simulation.

The latter overlays the impermeable metamorphic basement of phyllites and quartzites. A system of fractures is associated with the reservoir rock, but does not appear to be related to a particular layer or interface between layers. In Figure 11 the lithological profiles of Sp2 and several nearby wells are presented.

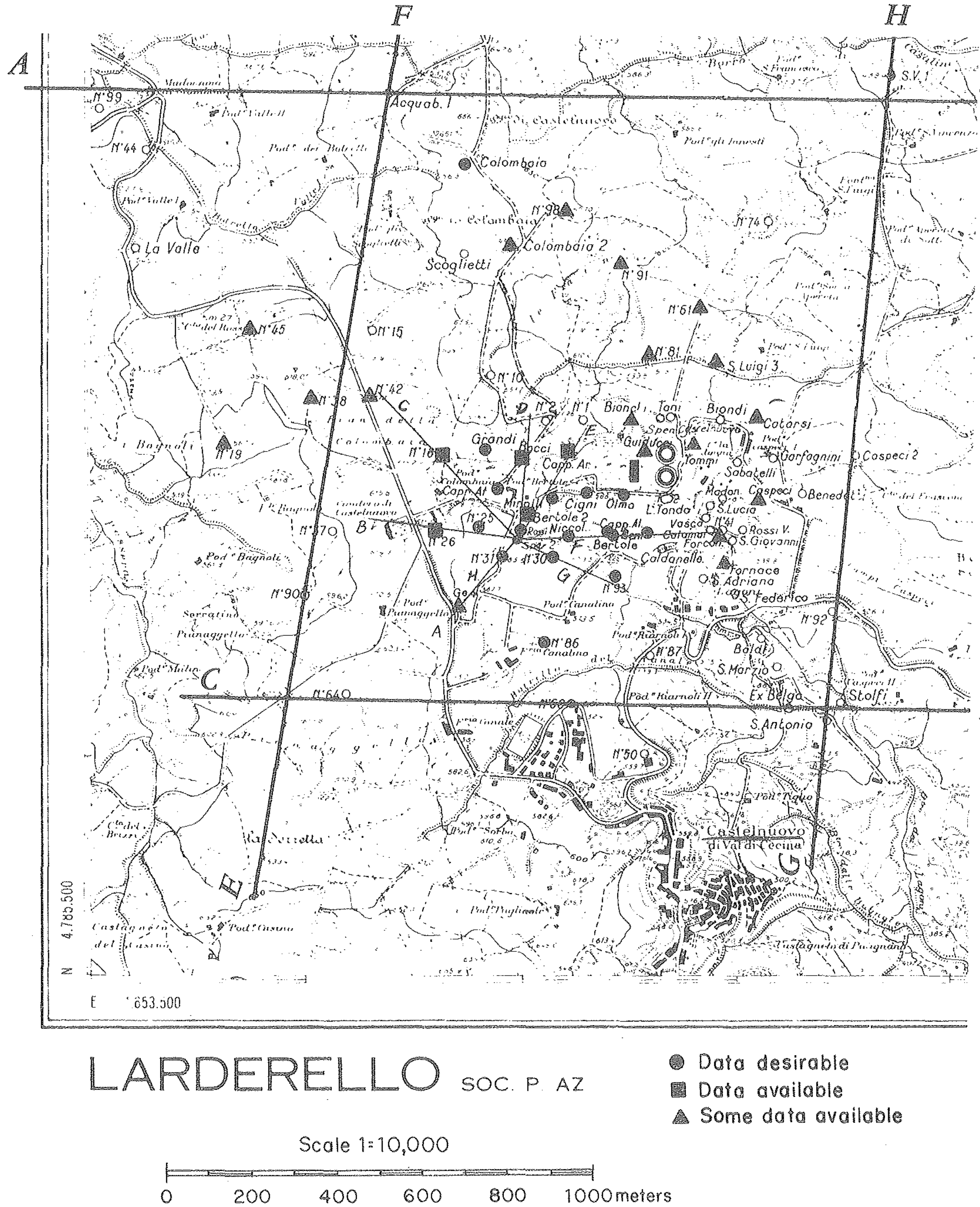
During the drilling of Sp2 a circulation loss occurred at 219.5 m and again at about 235.5 m, where a fracture zone was encountered. Drilling continued with fresh water injection to a depth of 861.5 m where another fracture zone was encountered. At this point the well was cased to a depth just above the deep fractures (830 m). Drilling then continued and water was injected into the deep fractures (830 m) until the final depth of 1,266 m was reached. At that point the injection and drilling stopped. In Figure 12 the flow rates are shown for Sp2, Bertole 2 and N16. The data cover the period from January 1974 to December 1975. During the injection in the shallow fracture zone in Sp2, the production pressure in Bertole and N16 follow the injection increases and decreases closely. After Sp2 was cased, while injection took place in the deep fracture system, no increase in procuction was apparent at the producing wells. This implies that there is little or no communication between the shallow fracture zone and the deep one during this time period. In Figure 13 the downhole pressure calculated from the wellhead values is shown for the period of injection in the shallow fracture zone. This pressure will constitute the test criteria for the computer simulation as described below.

COMPUTER SIMULATION OF INJECTION PHENOMENA

Two discrete representations of the Castelnuovo reservoir will be used. The first grid has been generated and approximates the Castelnuovo lithology as a single porous layer. The number of elements in this grid is 170 and the number of connections is about 370. (The number of elements in the grid in 157, but there are 13 more "source" elements which are not shown.) This problem is small enough to be run using the small-core memory version of SHAFT, and therefore could be used for calculational studies before the large-core version of SHAFT was operational. These initial calculations have now been made, but the results have not yet been analyzed. This simple model for Castelnuovo is expected to provide initial insight into the phenomena that occur during the injection of cold water (~25^{o}C) into a vapor dominated system.

A second grid, which is now being constructed, represents the detailed geology of Castelnuovo, although the fractures will be represented by "effective" material parameters averaged over the element in which the fractures are found. The initial configuration for the three-dimensional grid is shown in Figure 14. This more accurate grid representation requires more than 200 elements, and will necessitate the use of the large-core version of SHAFT, which is currently being tested.

The computer simulation at Castelnuovo encompasses a much smaller total volume than the Serrazzano calculations. However, in the injection



XBL 784-642

Figure 10. Map of the Larderello Basin showing locations of wells.

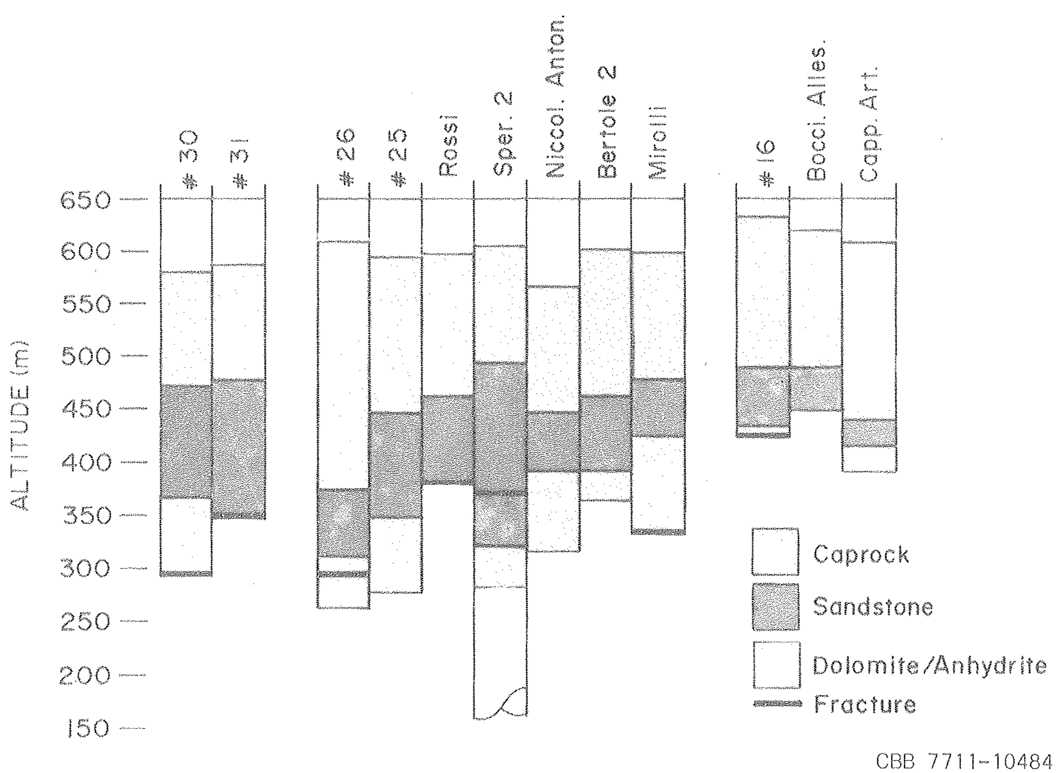


Figure 11. The Castelnuovo lithology as obtained from well logs.

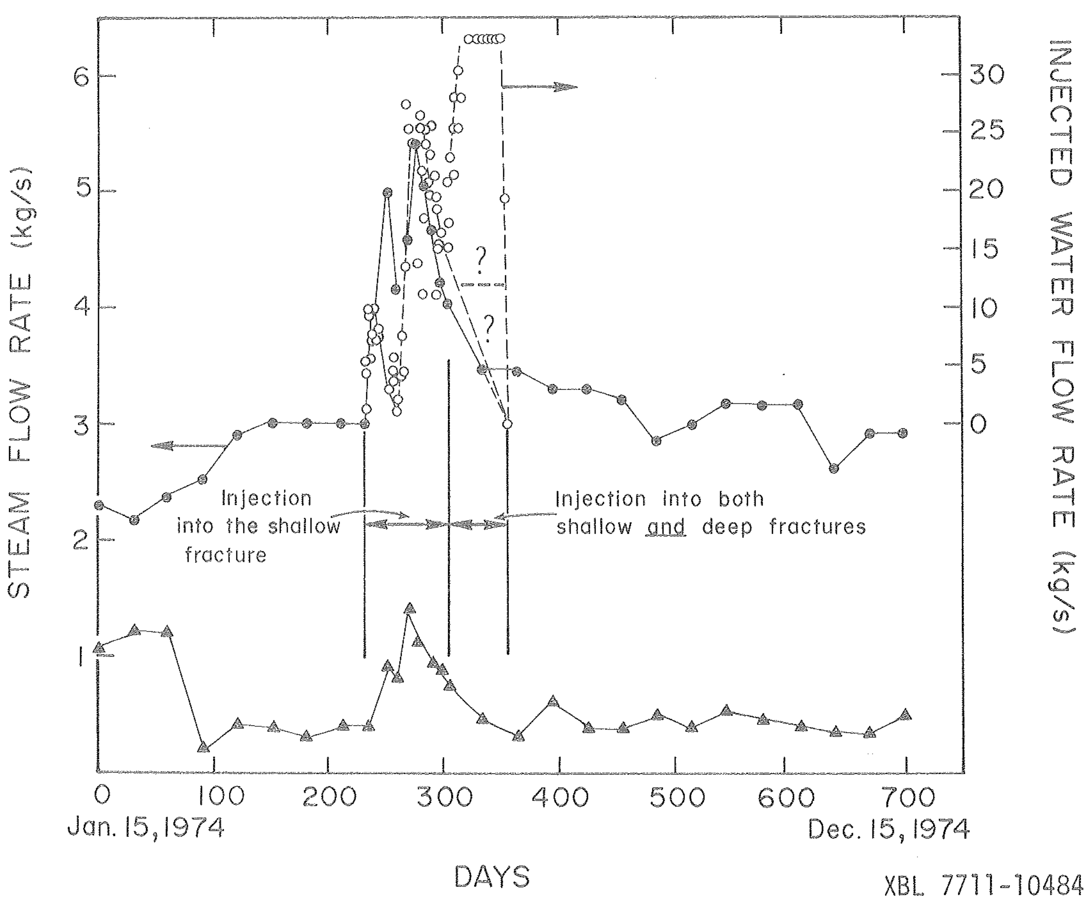


Figure 12. Flow rates at Castelnuovo. Water was injected into Sp2 (o) and was produced from wells Bertole 2 (●) and N16 (▲).

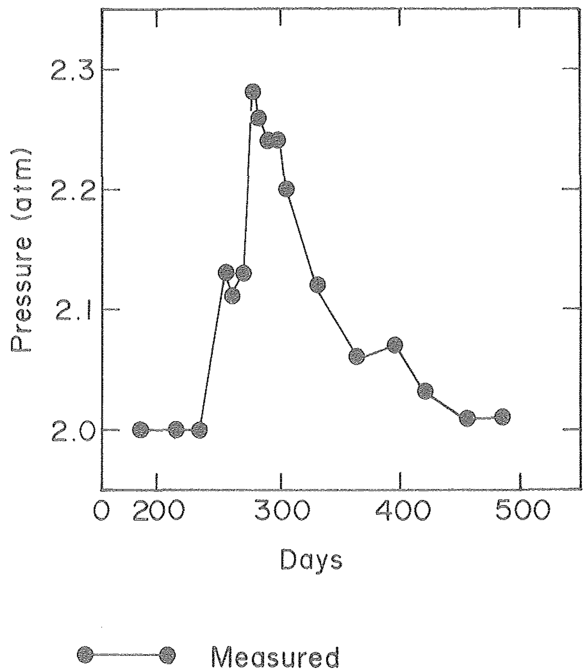


Figure 13. The downhole pressure in Bertole 2 calculated from measured wellhead values.

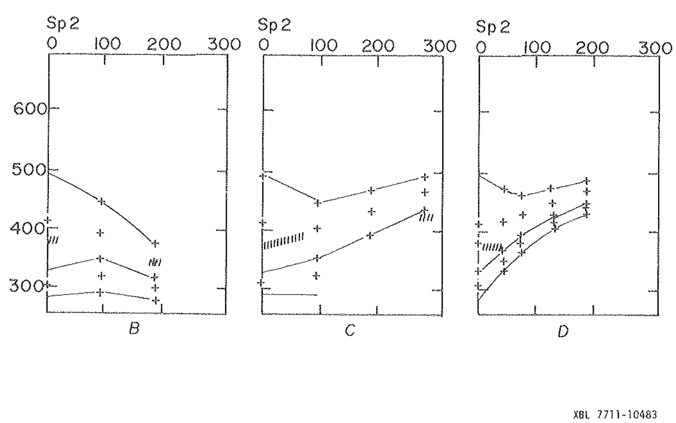


Figure 14. The Castelnuovo grid derived from lithological logs.

calculations the individual well behavior is being studied. To model the detailed production history with a time-scale in terms of days, rather than in months as for the Serrazzano simulation, requires finer coverage of the spatial geological system to provide an accurate history match with sufficient detail. As a result of the need for finer coverage, the number of elements in the injection simulation is almost as great as the number of elements for the entire reservoir simulation at Serrazzano. The choice of a grid representation with large numbers of elements is not a limitation unique to the SHAFT program or to the IFD method. Large grid elements would not be advisable in the injection problem when the purpose of the simulation is the detailed history match and subsequent examination of the physical processes which occur near the liquid-vapor interface during injection.

FUTURE WORK

The calculations using the two-dimensional grid will be completed and studied for any indications of model or computer program problems. The "best" choices for reservoir parameters and for the initial and boundary conditions will be estimated from the two-dimensional studies. This is an important consideration since the material parameters are not known at Castelnuovo, and the kh values estimated for Serrazzano[8] probably do not apply. The reason that they do not apply is that the Macigno formation is important at Castelnuovo but is not present at Serrazzano. The parameter estimates and initial and boundary conditions will be used for the final detailed calculations.

The simulation procedure for a history match of the injection/production data follows the same approach described in the section on Serrazzano. The flow rates and temperatures will be used as input to all the wells in the simulation. The computer program will calculate the corresponding pressure, density, and steam saturation at every discrete grid point. The calculated pressures at the well locations in the grid will then be compared with the measured pressure data.

These injection calculations have a dual purpose. First, to validate the physical model and computer program being applied to these two-phase problems; and second, to provide insight into the subsequent injection studies to be carried out during the Serrazzano reservoir simulation.

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Management Services

NSF/RANN LEGACIES

W. J. Schwarz and J. H. Howard

INTRODUCTION

The support of geothermal reservoir-engineering-related work, started under the NSF/RANN program and transferred to ERDA at the time ERDA was established, was in turn assigned to LBL in FY 1977. All contractors are conducting research related to improving exploitation of geothermal resources. These projects support DOE/DGE goals, particularly those of the Resource and Technology/ Resource Exploitation and Assessment Branch. The goals of this branch are to determine the magnitude and distribution of geothermal resources and to reduce the risk of their exploitation by characterizing the generically different kinds of reservoirs. This will be accomplished by: gathering and interpreting data, geophysical modeling of reservoirs, and mathematical modeling of reservoirs, utilization options, and demographic and economic factors.

1977 ACTIVITIES

Contracts negotiated and programs initiated during 1977 are shown in Table 1. Following is a summary of the tasks.

Table 1. Current NSF/RANN legacies contracts

PROJECT TITLE	CONTRACTOR
Data compilation and Analysis From Italian Geothermal Fields	Stanford-"Italian"
Modeling, Tracer, and Analytical Studies of Geothermal Resources	Stanford "Ramey-Kruger"
Wairakai Geothermal Reservoir Model	Systems Science and Software (S^3)
Mass and Heat Transport - Fractured Systems in Geothermal Reservoirs	Princeton
Modeling of East Mesa Geothermal Field	University of Colorado
Cerro Prieto Geothermal Modeling	UC/Riverside

<u>Stanford University "Italian" Projects</u>

The Stanford University "Italian" program which supports research for projects 3/3, 3/4, and 3/5 of the ERDA/ENEL agreement addresses the following tasks:

1. Carry out studies of reservoir pressure decline-curve analysis for the Serrazzano zone of the Larderello field (Project 3/3).

2. Conduct well-testing analyses of the Travale-Radicondoli field using new mathematical analytical procedures (Project 3/4).

3. Carry out a thermodynamic study of the Bagnore field at Mount Amiata, emphasizing anomalous well and reservoir pressures, high carbon dioxide content of wells, and consider the possibility of water encroachment (Project 3/5).

Quarterly reports for the following periods have been received from the program contractors: July 1 to October 1, 1976; October 1 to December 31; 1976; January 1 to March 31, 1977; April 1 to June 30, 1977, and July 1 to September 1, 1977.

A summary of the progress made in each of the three projects follows.

Project 3/3

Reservoir geology and pressure and production data for the period 1950 to 1977 have been studied. Methods for estimating reserves from decline-curves, which have been useful in forecasting oil productions from natural resources, were considered. Bottom-hole pressures and temperatures in productive wells have been calculated from wellhead measurements. Shut-in wellhead pressures have been plotted vs time. Using these results, area distributions of pressures have been mapped at seven times over the last 15 years. The field average was determined at these seven times and plotted against cumulative production from the field.

The results of these calculations are being applied to estimate the distribution of fluid pressures in the reservoir and to estimate the average reservoir pressure as a function of time.

Decline-curve analysis of individual wells was performed using a method developed by Fethowich. A straight-line relationship between p/Z (p = pressure, Z = gas compressibility factor and cumulative steam production) was established. Studies were made to interpret this relationship in terms of reserves. Pressure p in p/Z is the average of the wellhead pressures of shut-in wells while steam is being produced from other wells in the reservoir. Thus p could be taken as an average reservoir pressure. However, the extent of recharge was not known.

Enough work on the analyses of bottom-hole pressures and wellhead data was completed to permit the preparation of papers for presentation at the Larderello Workshop on Geothermal Resource Assessment and Reservoir Engineering, September 12-16, 1977.

Project 3/4

Pressure and production histories, pressure buildup data, and other well test data collected in this field were studied to design a well testing program. Pressure and production histories, pressure buildup data, and other well test data were studied to develop the best possible conceptual picture of the reservoir based on data now at hand.

A well testing program was designed and work was started in the development of a simple analytical model of the reservoir to be used as an aid in the estimation of reservoir size and configuration.

Measurements of shut-in pressures at wells across the field have been made twice a month since January 1977. A short interference test among the R8, T22, and T23D wells was run. The analysis of buildup and interference tests was carried out on recently drilled wells by the application of standard techniques to the data. The Horner buildup behavior of various new mathematical models has been evaluated in order to match the pressure buildup response of the T22 well. Other mathematical models involving a discontinuity in diffusivity were investigated.

Computer programs for the application of two numerical techniques to this problem have been developed. The first program was a compact, rapid and accurate algorithm for the numerical inversion of Laplace transforms. The second program was an efficient algorithm for solving the discretized form of the $\nabla^2 p$ operator over a particular bounded Cartesian region with a linear discontinuity in diffusivity. On April 26, 1977, the total production rate of the Travale reservoir was increased from about 170 tons/hr to about 220 tons/hr. This increase was needed in connection with new well-interference tests involving virtually all wells in the reservoir.

Two mathematical models of importance have been developed to account for the pressure buildup behavior of Travale well 22. In one of these models the reservoir was considered to be a composite system of uniform thickness. The central portion was assumed to have the shape of a vertical cylinder of fixed radius with a fully penetrating well coinciding with the axis of the cylinder. The remainder of the reservoir has the shape of a cylindrical annulus, its inner radius being the same as that of the central portion and its outer radius being large enough to account for the estimated size of the actual reservoir. Because the outer radius is open to question, it can be extended and can even approach infinity. The diffusivities were uniform in each portion of the reservoir but differed from one portion to the other.

In the second model, the reservoir was represented by a parallel-piped with one centrally located, fully penetrating vertical well. This well was in the center of a fully penetrating vertical fracture parallel to two sides of the parallelepiped.

A special report covering the Pisa Conference of September 1977 is now in preparation.

Project 3/5

The review of geology and of available pressure and flow data, begun during the summer quarter, was continued. Chemical and physical data as well as drilling records for the years 1959-1961 have been reviewed with the intention of defining the initial state of the reservoir. Cumulative production before installation of the power plant was estimated. A tentative plot of CO_2 partial pressure vs cumulative gas production for the years 1959-1961 showed a linear trend.

Material balance curves, for which the production of steam and carbon dioxide was considered independently, were graphed. These graphs show p/Z as a function of cumulative production. A straight-line relationship was obtained on the carbon dioxide graph. For the steam, p/Z vs cumulative steam production was a gentle concave upward curve sloping downward to the right.

A lumped parameter model of the reservoir was developed involving chemical and thermodynamic equilibrium for a reservoir rock-and-fluid system composed of water and steam, carbon dioxide, and calcium carbonate.

Stanford University Ramey-Kruger Project

The Stanford University Ramey-Kruger Project has addressed the following tasks:

1. Studies of phenomena of heat extraction including heat flux from fractured rocks and analytical modeling of thermal stress cracking.

2. Analysis of properties of the flow of geothermal fluids in porous media including capacitance probe studies, the effect of salinity on transition to different flow regimes, and relative permeability studies.

3. Studies of pressure transients.

4. Studies of radon as a natural tracer of fluid movement in geothermal reservoirs.

5. Formulation of improved mathematical models of geothermal reservoir behavior.

6. Organization of the Third Annual Stanford Geothermal Workshop held on December 14-16, 1977.

Interim reports were recieved on the following subjects in the Ramey-Kruger project.

Task 1. a. Heat flux from fractured rock. The application of the shaped rocks to the heat transfer model developed by Hunsbedt (1976) was studied. This will develop an analytical model to evaluate the energy extracted fraction from a geothermal reservoir of a given rock size distribution and under variable fluid cooling rates.
b. Modeling of thermal stress cracking. Experimental demonstration of heat transfer enhancement from geothermal rocks under thermal stress conditions were studied. This project will follow the proposed experiment to evaluate the heat transfer properties in the reservoir chimney model using the present granite loading with decreased porosity and permeability.

Task 2. a. Capacitance probe. This program obtains fundamental experimental data on steady and unsteady single and two-phase flow in porous media. This permits proper statement of pertinent physics of geothermal systems in large-scale reservoir simulators and calibration of computer simulator programs. Current work is aimed at studying the dielectric constant liquid content detector described by Dr. H.K. Chen.[1]
b. Vapor pressure lowering by capillarity. The existence of vapor pressure lowering in boiling of liquids in porous media has been explored. Both adsorption-desorption and capillarity effects are under study. This project is largely experimental in nature.
c. Temperature effect on permeability. The effect of temperature level on relative permeabilities to hot water and steam in geothermal systems is being explored. A major effect of temperature on absolute permeability to water was discovered; a decline of 50% in absolute permeability to single-phase flow of water was observed with a temperature increase from 70°F to 300°F. It appears a water-quartz reaction was involved.

Task 3. Pressure transients studies done under Prof. H. Ramey by looking at James technique. This task prepares methods for analysis of pressure transient data obtained in geothermal wells. Work on evaluation of Laplace transforms of solutions and the R. James "lip pressure" method of flow metering of geothermal steam were conducted during the last two quarters. Evaluation of the real gas potential for steam is under way.

Task 4. Radon. Radon has been developed as an internal tracer in vapor-dominated and liquid-dominated geothermal reservoirs to relate the emission rate of radon in the geofluid to the flow rate conditions in the reservoir.

Task 5. Radon emanation from geothermal reservoirs. The task covers the engineering and environmental significance of radon release by geothermal fluid. Emanation characteristics of radon from rocks under thermodynamic conditions in closed systems and the rubble chimney model have been explored.

A further progress report covering the last part of FY 1977 is in preparation.[2]

Systems Science and Software (S^3)

The S^3 projects are concerned with the following activities and tasks:

1. Collect pertinent data for Wairakei Field, and evaluate its accuracy and reliability.
2. Compile collected data into user oriented format.
3. Make recommendations for strengthening the data base.
4. Disseminate the compiled data bank.

FY 1977 progress on the S^3 projects includes the following:

1. Data on the heat discharge per well were assembled for the startup period (January 1953 to December 1974). Temperature loss data were compiled and the USGS data base (emphasizing pump test information) was reviewed.

2. At Wairakei, well location and geometry data, miscellaneous production data, surface heat flow and temperature survey charts, well logs, pressure data, ground motion surveys, and various other miscellaneous information were acquired.

3. Information is being compiled to include a geologic profile of each well, its location and the intervals open to production. The mass and enthalpy production data have been prepared in both tabular and computer-tape format. The available pressure and temperature histories have been prepared to be included in the final report of this contract. There is also some fragmentary surface heat flow data which have been examined; they too will be included. Subsidence data have been collected and will be presented in a sequence of maps and tables.

4. Colin Maiden, Chairman of the New Zealand Energy Research and Development Committee, visited S^3 on 8 September 1977 to inquire about the project.

Princeton University

The Princeton University program comprises the following tasks:

1. Fractured Reservoir simulation:
   Complete the formulation of fractured reservoir flow, develop computer code for such formation;
   Demonstrate application of the model to an Icelandic field situation;
   Extend fractured reservoir model to multiphase flow.

2. Conduct subsidence simulation:
   Develop an isothermal multiphase simulator for subsidence;
   Extend to non-isothermal case;
   Apply, if possible, simulator to a subsiding geothermal field.

3. Improvement in simulation techniques such as assymetric weighting schemes subroutine for two-phase transport.

Project progress in FY 1977 included the completion of the theoretical formulation of the fractured reservoir model. The associated computer program, designed to solve the fractured reservoir equations, is operational and has been tested for a series of simple problems. The multiphase subsidence simulation is operational and selected sample problems have been examined. The accuracy of the computer code, its application, and its limitations have been established.

Asymmetrical weighting functions have been introduced into the finite element model. The documented computer code for the iterative finite element method was completed.

In addition a publication, based on the contract, entitled "Calculation of the Flow of Liquid and Heat in Fractured Porous Media" No. 77-W-18 was received in November 1977.[3]

University of Colorado

The University of Colorado program concentrates on the following tasks:

1. Refine the conceptual physical model of the East Mesa field.
2. Continue analyses of heat and mass transfer in fault zones including changing of aquifers fed from the fault zone and heat transfer through caprock.
3. Apply numerical modeling programs to study of the East Mesa anomaly in an effort to define the geothermal reservoir system parameters and to evaluate optimum energy extraction schemes.

A progress report of fiscal year 1977 activities is in preparation.

The University of California at Riverside

The program at the University of California at Riverside encompasses the following tasks:

1. Inventory all cores and cuttings from Cerro Prieto field; select certain cores and cuttings for study
2. Prepare detailed petrological logs of wells; compare same with electric logs being done at LBL
3. Perform stable isotope analyses of fluid samples from the field in coordination with USGS and relate to lithologic studies
4. Select "best" well for detailed study leading to understanding of geothermal aquifers in Cerro Prieto
5. Develop preliminary model of subsurface geology of field
6. Develop preliminary statement of nature and extent of hydrothermal reaction in subsurface, noting in particular loss of porosity

A progress report for the period through 5 October 1977 was received on 12 October 1977. Several visits to Cerro Prieto for exchange of information and collection of samples have been made.

Cuttings and core samples were obtained from six new wells drilled in 1977. Initial lithologic descriptions of all these wells, using the binocular microscope and thin sections, are either complete or nearly so. Detailed petrographic work was done on some of the wells. The work, varying in extent, revealed the presence of three major hydrothermal mineral assemblages:

1. A potassium-silica assemblage, characterized by hydrothermal quartz, K-feldspar, K-mica, chlorite, and pyrite
2. A calcium-aluminum silicate assemblage characterized by epidote/clinozoisite prehnite, tremolite/actinolite, and biotite (?)
3. A carbonate assemblage consisting predominantly of calcite but sometimes including anhydrite, pyrrhotite, and/or purite.

These assemblages are related both spatially and temporally and should prove to be mappable through the field. Additional work in progress includes systematic x-ray diffraction analyses of a number of wells at intervals of about 25 m. These studies have shown that the nature of water/rock reaction in the PRIAN No. 1 and M92 wells indicates that these wells are cold and of low permeability; wells M90 and M91 show much better permeability and should have moderate to high temperatures. However, wells M48 and M84 show a high degree of alteration and should exhibit high temperatures and steam productivity. These findings implied that the predominantly steam field does not extend as far east as PRIAN No. 1 or as far south as the M92 well.

PLANS FOR FISCAL YEAR 1978

As a result of the fiscal year 1977 activities, all but one of the NSF/RANN legacy contracts have been or will be extended into fiscal year 1978.

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GEOTHERMAL RESERVOIR ENGINEERING MANAGEMENT PROGRAM PLAN

W. J. Schwarz and J. H. Howard

The Geothermal Reservoir Engineering Management Program (GREMP) Plan touches on almost all technical areas involved in the exploitation of geothermal resources. It funds subcontractors to conduct research investigations and monitors these projects while they are in progress.

GREMP was conceived in direct support of the DOE/DGE mission, which is to develop more on-line power sources. In particular, it supports the goals of the Resource and Technology/Resource Exploitation and Assessment Branch, which are to determine the magnitude and distribution of geothermal resources and reduce risk in their exploitation through an improved understanding of generically different reservoir types. These goals are to be accomplished by the creation of a large and accessible data base on geothermal reservoirs, improved tools and methods for gathering data on geothermal reservoirs, and modeling of reservoirs and utilization options.

Planning for GREMP was initiated in October 1976. The GREMP document[1] was completed and published at the end of FY 1977. The development of the plan included the following research tasks: 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 to improve this status; and 3) the formulation of a plan of action to achieve such improvement, including identification of appropriate research projects with their schedules and milestones, priorities based on the need for results, and as complete and specific an explanation of proposed research projects as possible.

The planning process for GREMP involved organizing a Program Planning Team and a Review Task Force, conducting a literature survey, evaluating the state of the art, identifying research needs, defining research projects, acquiring recommendations from the Review Task Force to incorporate into the overall plan, and publishing the GREMP planning document.

The Program Planning Team referred to above consisted of members with broad experience in the field so that they could identify the desirable elements of geothermal reservoir research and develop a program plan.

The Review Task Force was separately formed to review and make recommendations for improvements in the program plan. This group met to review the draft GREMP document during fiscal year 1977 with regard to its completeness and its ordering of research priorities. As expected with a group coming from diverse backgrounds and having different interests, a unanimous opinion on priorities was not reached. Nevertheless, the group did reach a general consensus about the assignment of priorities.

The elements that make up the GREMP plan and the priorities recommended by the Task Force are (in descending order of importance):

1. Well testing
2. Interpretive borehole geophysics
3. Geochemical techniques and problems
4. Properties of materials
5. Numerical modeling
6. Site specific studies
7. Fundamental studies
8. Analytical modeling
9. Surface geophysics
10. Physical modeling
11. Economics
12. Exploitation strategy

The GREMP document was used as an internal planning tool in FY 1977 and will be so used again in FY 1978 and FY 1979. It is also a guide for potential contractors who may bid on various GREMP elements during FY 1978 and FY 1979, because it contains detailed technical descriptions of each element, a table of possible projects and tasks, FY 1978 and FY 1979 schedules, information on the procurement cycle, and contract negotiations.

GREMP elements are put up for bid in the order recommended by the Task Force. (It should be noted that responsibility for Interpretive Borehole Geophysics, which is the second priority element, has been transferred to LASL.) Open bidding announcements for the areas of Well-Testing, Geochemistry, and Properties of Materials were placed in the Commerce Business Daily on October 21, 1977. Requests for proposal for Well-Testing were mailed to over 80 potential contractors on December 21, 1978. Requests for proposals for Geochemical Techniques and Problems, and Properties of Materials were mailed to over 80 potential contractors between the beginning of January and ending of February. Depending on funding, plans should call for selecting contractors and initiating programs later in fiscal year 1978 for Numerical Modeling, Site Specific Studies, and Fundamental Studies.

A GREMP support program titled "Systems Engineering and Technical Analysis - the Area of Measurement Methods of Geothermal Reservoir Parameters" has been initiated with the Measurement

Analysis Corporation and is scheduled for completion by September 1978. Requests for proposals for an Annotated Research Bibliography for Geothermal Reservoir Engineering were mailed to numerous potential bidders in November 1977. Proposals have been received, evaluated, and negotiations initiated. The program is expected to be initiated and completed during fiscal year 1978. Discussions for a program entitled "Evaluations of Computer Costs for Geothermal Reservoir Modeling" with the Jet Propulsion Laboratory (JPL), contractor of NASA, have been started.

During fiscal year 1979 all the GREMP elements conceived in the plan should be funded and existing fiscal year 1978 contracts extended. A number of small additional GREMP satellite programs are planned for fiscal year 1979.

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FIRST ANNUAL WELL TESTING SYMPOSIUM, OCTOBER 1977

T. N. Narasimhan, R. C. Schroeder, and W. J. Schwarz

During October 19 through 21, 1977, the First Annual Well Testing Symposium was held at the Clarement Hotel in Berkeley. It was sponsored by the U.S. Department of Energy, Division of Geothermal Energy, through the Earth Sciences Division of Lawrence Berkeley Laboratory.

This symposium recognized the importance of geothermal reservoir assessment and the leading role therein of well testing. During the last ten years, the techniques and equipment for well-testing have undergone a phenomenal development. The symposium was held to evaluate the state-of-the-art of well-testing in general and its application to geothermal systems in particular.

Over 150 invited persons participated in the symposium which brough together well-testing experts from the fields of geothermal energy, the oil and gas industries, and ground water hydrology. The invited participants from these three disciplines were chosen to provide coverage of instrumentation, technique development, and well-test analyses. In addition to identifying problem areas where additional research and development are necessary, the symposium's aim was to unify the ideas and methods, where possible, in the three different disciplines.

Lawrence Berkeley Laboratory has been actively engaged in testing geothermal wells for about three years and has recently embarked on testing hard rocks of extremely low permeability for locating possible sites for storing high level nuclear wastes. In the spring of 1977 it was felt by the Reservoir Engineering Group at the Lawrence Berkeley Laboratory that currently there exists many challenging problems for which well-testing is potentially a tool of utmost importance and that there exists an urgent need to assess our current state-of-the-art in well-testing, primarily with a view to advancing the science to meet the newly posed challenges. It was immediately recognized that for such an assessment to be meaningful, there must be a cross fertilization of ideas between hydrogeology, petroleum engineering and geothermal engineering in regard to the theory of well tests. Moreover, a great deal of input is also imperative from other investigators such as those who design instruments, geophysicists who carry out borehole logs of many different kinds, drillers, packer experts and others. In this symposium an attempt was made to assemble a group of active workers involved with various phases of well-testing and drawn from various disciplines to provide a forum of discussion for the important problems related to well-testing.

The presentations made during the symposium can be broadly classified into five categories: Reviews, Instrumentation, Field Applications, Theory and Techniques, Drilling and Related Activities.

In his keynote address, Paul Witherspoon (LBL) briefly traced the history of well-testing by chronologically recalling the significant contributions from the hydrogeology and petroleum literatures. This presentation was embellished by many lively comments by Henry Ramey of Stanford University and this set the pace for the entire conference that followed. In all, three review papers were presented. Henry Ramey surveyed the status of transient well-testing in petroleum engineering with special emphasis on the producing well. E.P. Weeks of the U.S. Geological Survey made a comprehensive and up-to-date review of the literature on the state-of-the-art of well-testing in hydrogeology. A detailed study of the various theories available for studying near-well fractures was presented by R. Raghaven of the University of Tulsa. Over twenty technical presentations were made, followed by a brief panel discussion.

The panel discussion took place at the end of the conference. The panel included William Brigham, Myron Dorfman, George Miller, Ron Schroeder (LBL), William Walton and Edward Weeks, and was moderated by Jack Howard (LBL). The points that were made during this discussion included: the possibility that geothermal systems may be "leaky"; the importance of vertical permeability in geothermal systems; the need for the use of tracers in well tests; the utility of computer-aided applications; the importance of blending geology and geophysics with hydraulics; and the problem of water chemistry related to well-testing.

During a banquet held at the symposium, Arthur C. Wilbur, Director of the Geothermal Energy Department in DOE's San Francisco Operations Office, discussed the federal government's role in furthering the development of geothermal energy.

It was the opinion of the majority of attendees that a similar symposium should be held at about the same time next year. The organizing committee is currently considering a Second Invitational Well-Testing Symposium for the fall of 1978.

SUBSIDENCE RESEARCH

DEVELOPMENT AND PROGRAM MANAGEMENT

T. L. Simkin

INTRODUCTION

This program takes a major research issue, potential subsidence from geothermal energy production, and develops a comprehensive research program to investigate it. The program consists of research projects which have been prepared so that they may be subcontracted to selected capable organizations. Two separate public announcements have been made requesting organizations to submit "Qualification Statements" to LBL for consideration.

Two teams of professionals were used in 1975 and early 1976 to develop the program plan. One team prepared the plan; the other reviewed the plan and recommended changes. The program planning team consisted of Lawrence Berkeley Laboratory personnel with technical support from key non-laboratory individuals. The review team was composed of individuals from industry, academic, and government organizations.

The results of the research program plan development has produced a Lawrence Berkeley Laboratory document (LBL-5983) entitled "Geothermal Subsidence Research Program Plan," published in 1976.[1] The research plan defines activities for a four-year schedule. Thus, at this writing several research programs have been undertaken.

A workshop is planned for the fall of 1978 to review the "mid-point" results and to better define activities planned for 1979 and 1980.

Rationale

New energy sources must be developed. Under the direction of the Department of Energy (DOE), the development of energy sources is moving ahead in a number of fields, such as solar, geothermal, coal, and nuclear energy. Many opportunities are available for development of the resources; however, there are problems. One such problem is land deformation that may accompany removal or injection of fluids from or into geothermal reservoirs. The issue of land deformation, commonly referred to as subsidence, is the focus of this research program plan.

Unexpected and uncontrolled subsidence may have social, environmental, and economic consequences. However, subsidence occurring under controlled conditions may be acceptable. In addition, potential geothermal resource areas may be found in many different geological and land-use settings. Thus, subsidence may or may not be an issue of major concern. The degree of concern attached to subsidence will depend on an assessment of subsidence potential at each geothermal site.

Program Objective

The objective of geothermal subsidence research is to control or mitigate potential subsidence associated with geothermal development within predictable limits. In this way, geothermal programs may proceed without delay and siting flexibility may be increased.

Successful subsidence reasearch will provide the means for developers to build and operate geothermal facilities within prescribed limits of potential subsidence, and the basis for policy makers to regulate geothermal facilities with respect to potential subsidence.

Research Program Structure

The ultimate goals of the subsidence research program are to understand and control subsidence associated with geothermal energy development. Stated more precisely, these goals are to distinguish naturally occurring subsidence from that possibly caused by geothermal operations, and to operate a geothermal well field in a manner that will prevent or minimize adverse effects due to subsidence. Both goals are assessed to be achievable within the structure of the research program created by this plan.

The Subsidence Research Program is an integrated structure consisting of five major elements:

Characterization of Subsidence
Physical Theory of Subsidence
Properties of Materials
Simulation of Subsidence
Subsidence Control

These elements contain research categories, which define the thrust and direction of the research program. Research categories in turn are composed of individual research projects. The three levels of the program are illustrated in Figure 1. The number of components in each level varies with the research subject matter. For subsidence there are

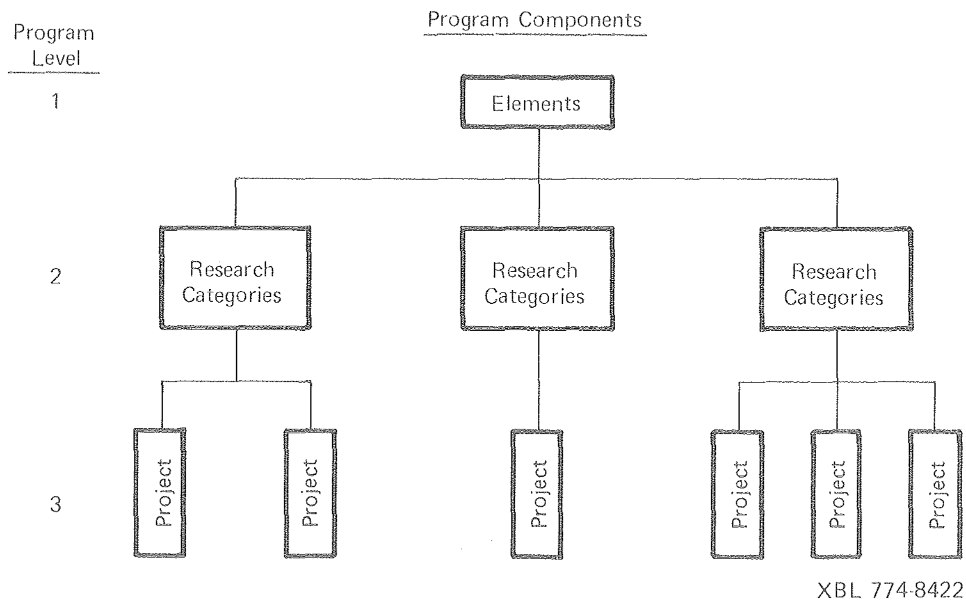

Figure 1. General research program structure.

five program elements, nine categories, and sixteen projects. The elements and their research categories are described below.

CHARACTERIZATION OF SUBSIDENCE

This structural element is concerned with the measurement of subsidence and subsidence effects. The intent of its research categories is to characterize the subsidence phenomenon or provide the means to attain that characterization. The element consists of four research categories:

Case Histories of Subsiding Areas and Geothermal Subsidence Potential Maps

As the name implies, the category involves research to document cases of known subsidence and mapping areas of geothermal subsidence potential. The research will provide knowledge of subsidence potential in different geological environments.

Field Measurement Programs

Subsidence baseline monitoring surveys (e.g., horizontal triangulation, vertical leveling) are needed to measure the degree of subsidence due to geothermal activities as opposed to other man-induced or natural subsidence, and to establish the background rate of land deformation. This category is concerned with providing baseline monitoring information in known and prospective geothermal areas. Much of the work associated with baseline monitoring is the responsibility of federal agencies, such as the National Geodetic Survey and the U.S. Geological Survey. These agencies are engaged in monitoring surveys at or near geothermal areas. This research category will assure that the surveys provide comprehensive and timely monitoring information.

Direct Monitoring Instrumentation

Direct observations at depth are necessary to relate subsurface compaction to surface subsidence. Such observations require instrumentation to accurately measure vertical distances between points in wells and drill holes. The development of such instrumentation is the subject of this research category.

Environmental and Economic Effects

Subsidence is a problem in geothermal development only to the extent that it produces undesirable environmental and economic consequences. Hence an understanding of possible effects from subsidence in different settings is essential. This research category is concerned with collecting economic data and investigating the effects of potential geothermal-related subsidence.

PHYSICAL THEORY OF SUBSIDENCE

Sound physical theory is a vital element of any technical research effort. Research to understand the physical processes that cause subsidence belongs in this research element.

Physical Processes of Subsidence

This category involves assessing current theory about the physical processes of subsidence and to correct deficiencies in that theory. The theoretical studies will include both the response of geologic materials to stress fields and the nature of induced movements along fracture systems.

PROPERTIES OF MATERIALS

Subsidence is a response of geologic materials to some external perturbation such as the removal of geothermal fluids. The element "Physical Theory of Subsidence" dealt with responses by perturbed materials. This element deals with the material properties that affect those responses. This element contains two research categories:

Indirect Measurements

Certain physical properties of geothermal reservoirs, such as porosity, flow rate, and pressure, may provide indirect evidence of compaction. If these properties are monitored over time, they could be used as subsidence indicators within the reservoir. However, in most cases the instruments or techniques needed to monitor reservoir properties are inadequate or nonexistent. This research category involves developing and testing instrumentation that will accurately measure certain reservoir properties. The identity and monitoring specifications of these properties will depend on a subsidence model. This model will use physical theory that relates the properties to reservoir deformation.

Laboratory Testing

At present some properties of geothermal reservoirs are not directly measureable in the field. These properties include characteristics of the rock materials such as compressibility, permeability, and chemical reactivity. In order to measure such characteristics, a laboratory testing program using actual samples of materials is required. Thus the purpose of this research category is to produce a testing program that will give realistic measurements of material properties under simulated reservoir conditions. The measurements will provide valuable input to rock mechanics subsidence models.

SIMULATION OF SUBSIDENCE

Simulation includes the mathematical modeling of subsidence and related phenomena. It is simply the useful application of physical theory. One or more reliable subsidence models comprise an essential element of the overall research program.

Subsidence Models

A number of subsidence models for geothermal reservoirs exist, but the applicability of these models remains in doubt. This research category

Table 1. The three levels of the subsidence research program.

Elements	Research Category	Projects
A. Characterization of Subsidence	1. Case Histories of Subsiding Areas and Geothermal Subsidence Potential Maps	1. Land Deformation Case Histories 2. Geothermal Subsidence Potential Maps
	2. Field Measurement Programs	1. Criteria to Distinguish Between Potential Subsidence Caused by a Geothermal Project and Subsidence Due to Other Causes 2. Monitor Horizontal and Vertical Displacement
	3. Director Monitoring Instrumentation	1. Assess the State of the Art 2. Develop Prototypes and Conduct Field Tests
	4. Environmental and Economic Effects	1. Data Collection 2. Investigate Effects
B. Physical Theory of Subsidence	5. Physical Processes of Subsidence	Same as Research Category
C. Properties of Materials	6. Indirect Techniques to Estimate Subsidence at Depth	1. Assess Indirect Techniques 2. Develop Prototypes
	7. Laboratory Testing	Same as Research Category
D. Simulation of Subsidence	8. Subsidence Models	Same as Research Category
E. Subsidence Control	9. Reservoir Operational Control Policy	1. Industry Evaluation 2. Guidelines and Procedures

supports studies to critically evaluate subsidence models and test them against hypothetical and actual field cases. If necessary, improvements to existing models or new model development may be included, pending the results of model evaluation.

SUBSIDENCE CONTROL

The last element is the target element of the research program. Within this element the program goals are attained. The other elements simply provide the supporting information needed to make those goals attainable.

Reservoir Operational Control Policy

This category includes background studies of reservoir management practices leading to the development of operation policies that minimize the effects of subsidence. Such policies are formulated with knowledge gained from the total research effort (e.g., models, baseline measurements, laboratory tests) and represent the culmination of that effort. Inherent in these policies are the abilities to separate natural from man-induced subsidence and then mitigate the man-induced portion.

The subsidence research program structure, including individual research projects, is illustrated in Table 1. Detailed specifications for the categories and projects are given in Appendix B of the Geothermal Subsidence Research Program Plan.[1]

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MODELING SUBSIDENCE DUE TO GEOTHERMAL FLUID PRODUCTION

M. J. Lippmann, T. N. Narasimhan, and P. A. Witherspoon

INTRODUCTION

Of the different types of geothermal systems in existence, only hydrothermal convection systems are currently being tapped for energy. These systems occur where circulating water and/or steam transfer heat from depth to the near-surface. A few of them may be vapor-dominated and produce saturated, or even supersaturated steam (for example, The Geysers, California). But most hydrothermal systems deliver a mixture of hot water and steam at the surface. These are the so-called liquid-dominated systems (for example, East Mesa, California and Raft River, Idaho) which are characterized at depth by the occurrence of saturated, porous or fractured rocks containing hot water which controls subsurface fluid pressures and stress changes. The results of resource assessment studies indicate that hot-water systems hold the maximum promise for developing geothermal energy in the United States.[1]

A characteristic of these hot water systems is that they may experience significant reductions in pore fluid pressures as a consequence of large-scale production of geothermal fluids. Pressure decrease in the reservoir and surrounding water-saturated formations may cause appreciable rock deformations leading to surface displacements. For example, significant surface deformations have already been observed over the Wairakei and Broadlands geothermal fields of New Zealand[2,3] and are suspected to occur in Cerro Prieto, Mexico.

Because ground displacements may affect engineering structures related or unrelated to the operation of the geothermal field, it is important to be able to foretell the pattern and magnitude of the deformations that may result from fluid production, to introduce preventive or remedial actions. The objectives of the project reported here, which began in September 1975, are to develop numerical models to compute ground displacements caused by pore pressure reduction in geothermal reservoirs and to examine the significance of different parameters affecting geothermal system deformation.

ACCOMPLISHMENTS FOR 1977

New features were added to the LBL "Conduction, Convection and Compaction" (CCC) computer program[4,5] which simulates the transport of heat and water through porous media, including the vertical displacements resulting from pore pressure changes. First, a more general equation of state for the fluid was incorporated treating the water density as a quadratic function of temperature and pressure. Second, the code was modified to include thermal and hydraulic anisotropy, when the principal axes of anistropy are parallel to the coordinate axes. Finally, new input-output capabilities were added to the program.

During this year, a number of hypothetical cases were analyzed to study the effects on reservoir compaction of several of the parameters used in the energy and mass transfer equations.

An axisymmetric three-layer system (Figure 1), with a producing well at the axis of the reservoir, was chosen to illustrate the role of non-linear, non-elastic deformation parameters on reservoir compaction (Figure 2) and the relation between subsidence history and reservoir pressure.[6] The response of the system to 20 days of pumping at a rate of 2.5×10^6 kg/day is shown on Figures 3 and 4. Curves a and b correspond to overconsolidated materials with two different magnitudes of overconsolidation. Initially, at each point in the system the effective stress is smaller than the preconsolidation stress. Curve c describes the behavior of a normally consolidated system in which, at time

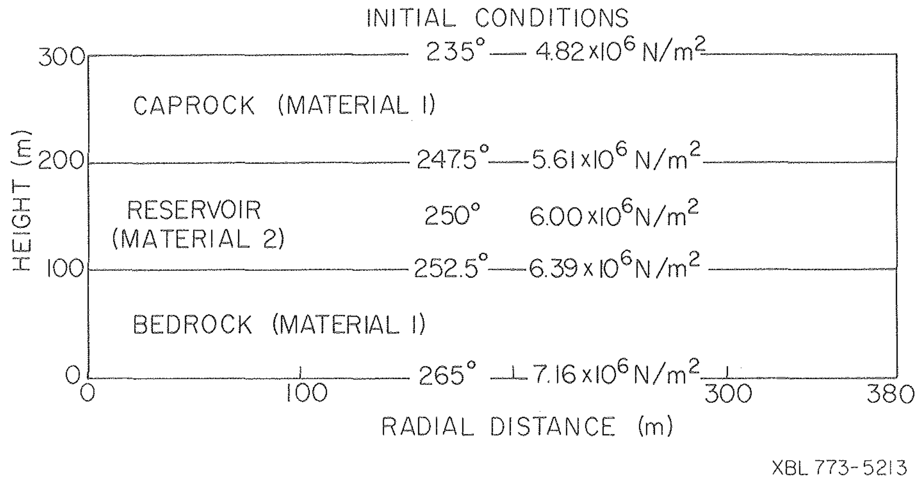

Figure 1. Three-layer system: geometry and initial conditions.

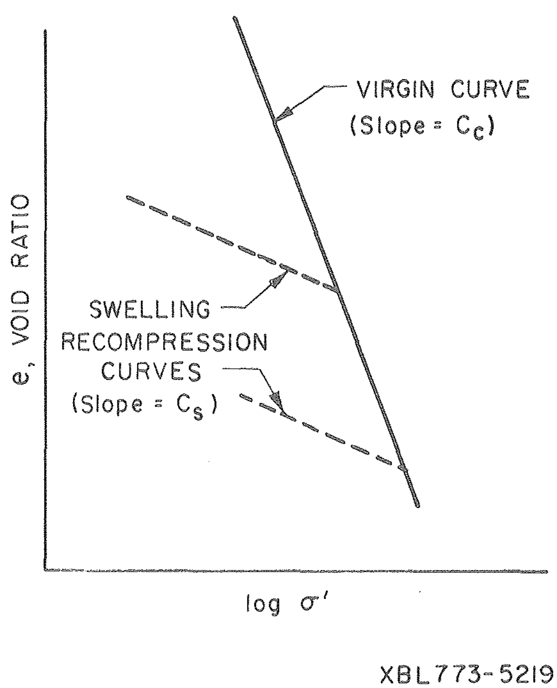

Figure 2. Plot of void ratio (e) versus effective stress (log σ') for a hypothetical material.

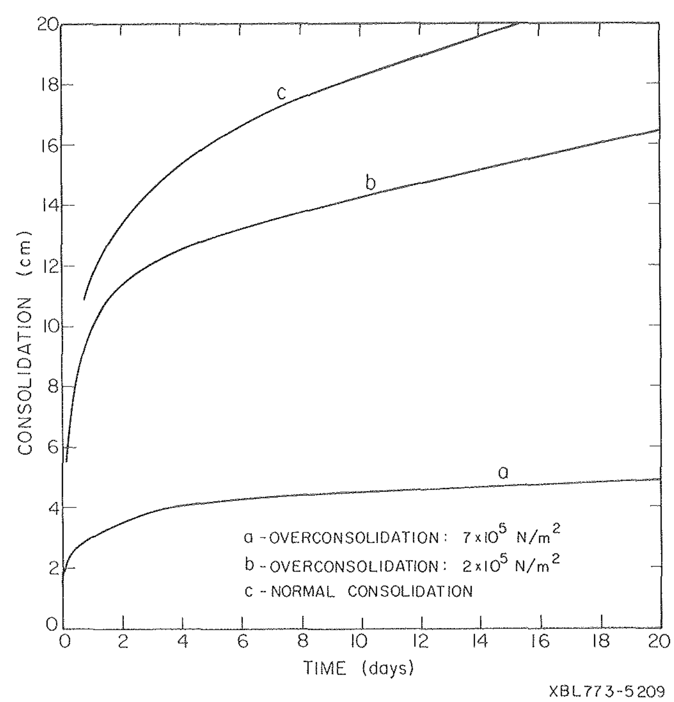

Figure 3. Three layer system: plot of vertical compaction versus time under different initial overconsolidation conditions.

zero, effective stress is equal to the preconsolidation stress at each point in the system.

For curve a, the overconsolidation is equal to 7 x 10^5 Pa. Because of this high value the deformation of the system is relatively small (Figure 3), with the stress-strain behavior of the materials following the recompression curves (Figure 2). Very little water is obtained from the compression of the rock skeleton. The compaction of the reservoir is significant at the beginning of the pumping period, but later, compaction of the caprock and bedrock becomes much more important.[4] As can be seen in Figures 3, 4, and 5 the system continues to consolidate even after the pressure has stabilized in the reservoir, because we are

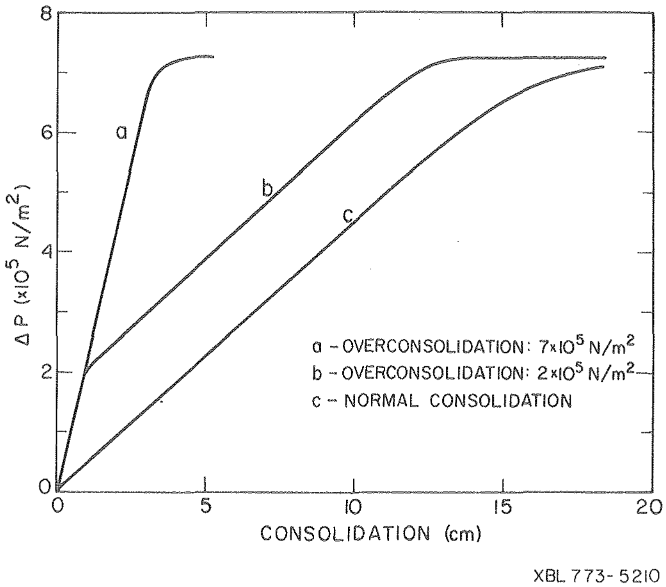

Figure 4. Three-layer system: plot of reservoir pressure versus consolidation under different initial overconsolidation conditions.

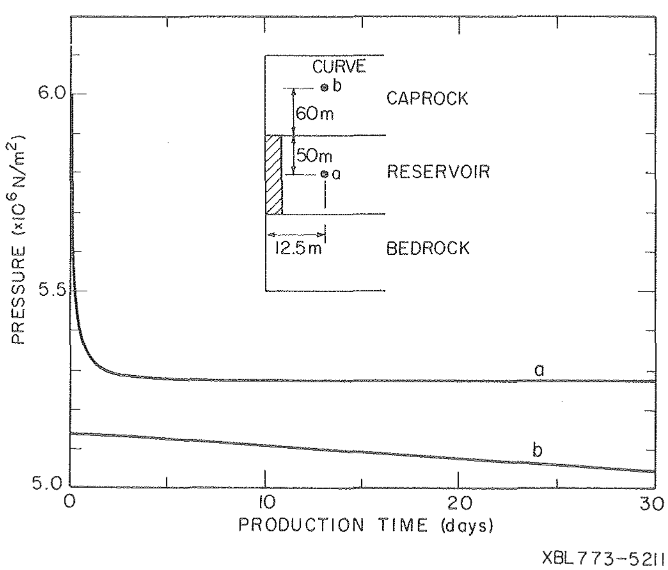

Figure 5. Three-layer system: pressure change versus time in reservoir and caprock for the case with overconsolidation = 7 x 10^5 N/m^2.

essentially concerned with a leaky aquifer system in which the more permeable material goes to a steady-state while in the less permeable caprock the pressure transients move very slowly in the vertical direction, outward from the aquifer.

Curve c in Figures 3 and 4 relates to a system under normal consolidation, which deforms according to the much steeper virgin curves (see Figure 2), leading to relatively larger magnitudes of consolidation. Curve b corresponds to an intermediate case, with a lesser overconsolidation of only 2 x 10^5 Pa. In this case, the materials deform at early times in accordance with the recompression curves. But, once effective stress exceeds the preconsolidation stress, the reduction in void ratio follows the virgin curves. This explains the intermediate behavior shown in Figures 3 and 4; curve b lies between curves a and c. Not only is the computed compaction different in each case, but also the response of the reservoir pressure is quite distinct.[5] This is emphasized when the pressure is plotted against the amount of consolidation (Figure 4). This graph clearly reflects the effects of differences in overconsolidation values and in the slopes of the virgin and recompression curves (Figure 2). The flattening out of the curves at the top is related to the constant pressure assumed at the radial boundary. The behavior of the system with an overconsolidation equal to 2 x 10^5 is quite interesting (see Figure 4, curve b). At the beginning it is identical to that of the system with a higher overconsolidation (curve a). When effective stress exceeds the preconsolidation value, the system deforms in a manner similar to that of the normally consolidated system (curve c). At this stage, curves b and c are essentially parallel. It is interesting to note that the response given by curve b (Figure 4) is similar to that observed in the Wairakei geothermal field of New Zealand, as shown in Figure 6, taken from Pritchett et al.[7]

The examples given above indicate that deformation parameters of the various materials present in the field should be established before one ventures to model subsidence in a given geothermal system. Laboratory techniques are available to measure the deformation properties of the rocks and their degree of overconsolidation. Field tests may establish the total stress and fluid pressures at different depths, as well as the prevailing boundary conditions. For a realistic field simulation, the aforesaid properties are of fundamental importance.

A two-layer system (Figure 7) was selected to illustrate the importance of analyzing compaction of geothermal systems using nonisothermal models and to study the effects of temperature-dependent fluid properties, anisotropy and material heterogeneities.[6] For this purpose a system with a caprock of variable thickness is considered.

The consolidation of the system after 2,400 days of pumping 2.8 x 10^6 kg/day under different conditions is shown on Figure 8. In the case of isotropic materials, the isothermal model has yielded higher consolidation than the non-isothermal one. This difference in behavior is essentially due to the constant average properties assigned to the isothermal system, while the non-isothermal one has temperature-dependent fluid properties. The variability of viscosity with temperature appears to have a considerable role in governing the consolidation of the non-isothermal system.[5] Figure 8 also shows two examples with anisotropic materials. In these, the radial intrinsic permeability (k) and thermal conductivity

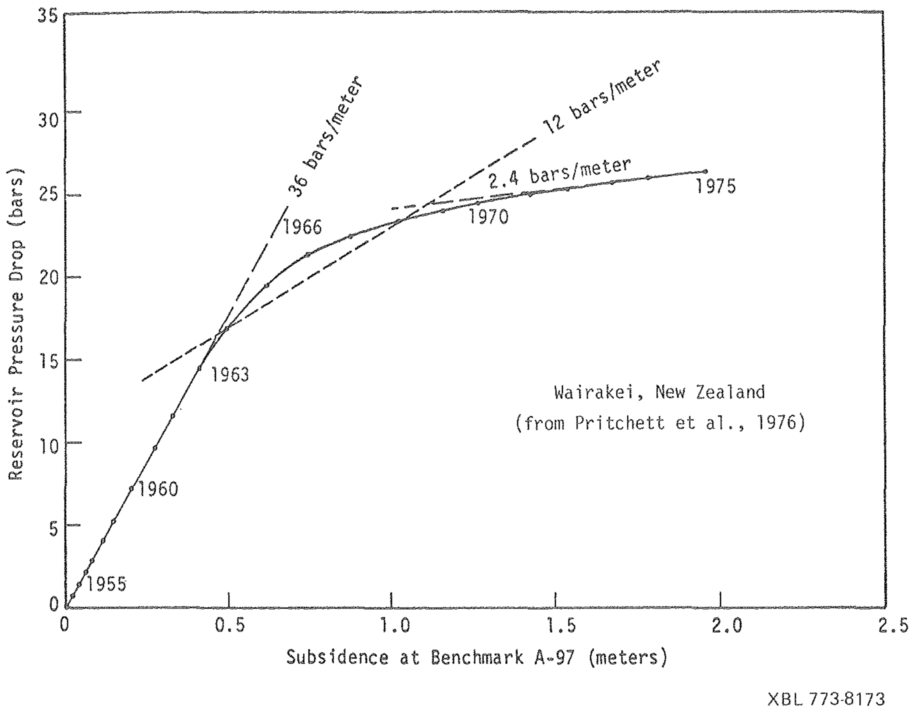

Figure 6. Reservoir pressure drop versus subsidence at Wairakei, New Zealand.

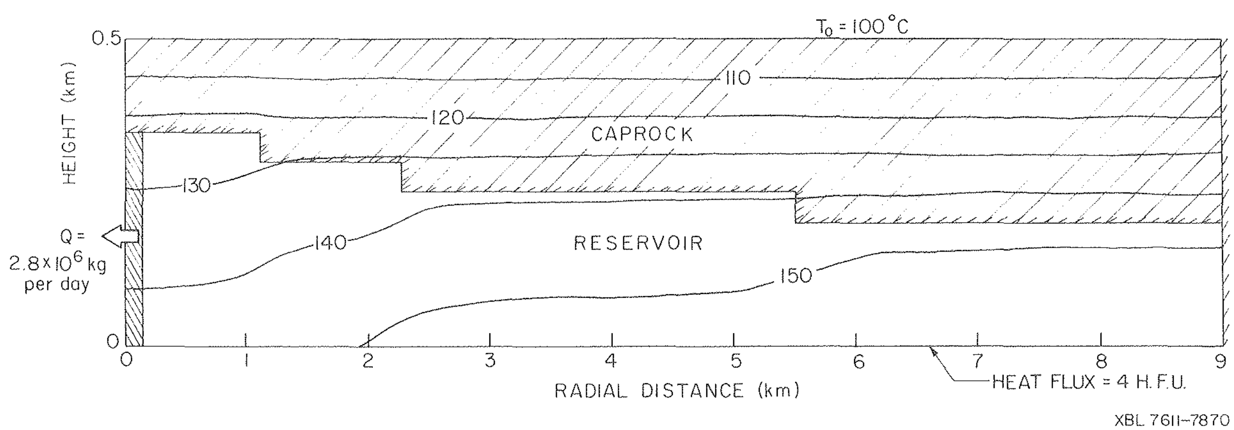

Figure 7. Two-layer system: geometry, initial and boundary conditions.

(K) are the same as in the isotropic case, but the vertical properties are reduced by a half.

From an analysis of the four curves shown on Figure 8 it can be concluded that:

(a) the use of isothermal models to simulate geothermal systems may result in predicting somewhat larger and more conservative consolidation values than in the non-isothermal case;

(b) higher temperatures (and lower fluid viscosities) in the system may reduce the magnitude of consolidation near the pumped well;

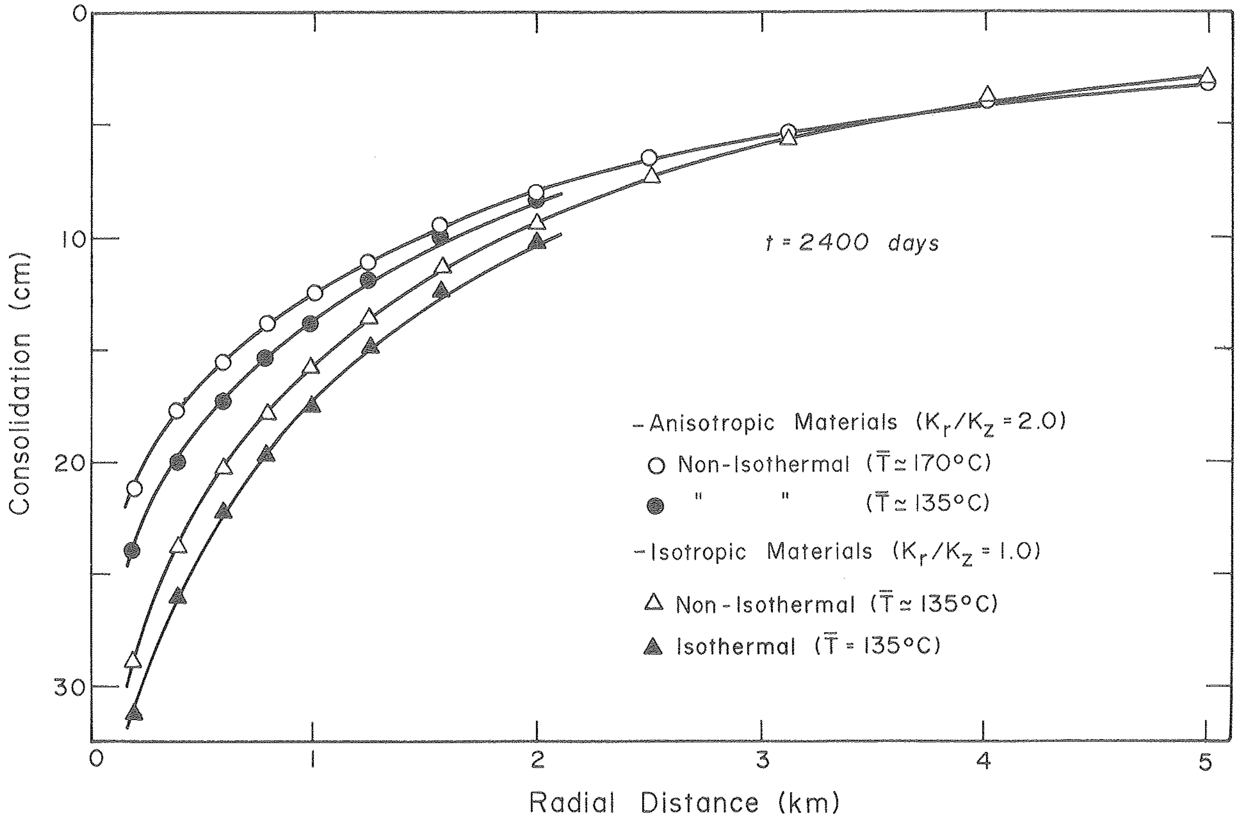

Figure 8. Two-layer system: effect of temperature and anisotropy on consolidation.

(c) the presence of anistropic materials tend to reduce the consolidation near the well, while slightly increasing consolidation away from it (the curves on Figure 8 cross each other at a large radial distance from the well).

The effect of geological heterogeneities is explored by introducing a lens of caprock material within the reservoir (Figure 9). Other conditions remain the same as in Figure 7. As can be seen from Figure 9, the presence of a compressible lens within the reservoir affects the tortuosity of flow path and the pressure distribution near the well, leading to a dramatic change in the profile of the subsidence bowl. Note that the maximum subsidence of about 38 cm occurs approximately 0.4 km away from the producing well. This simplistic model may perhaps provide a clue to understanding the interesting subsidence pattern at Wairakei (Figure 10), where the subsidence bowl is observed to be offset approximately 1.5 km east-northeast of the main producing area. In the light of the results presented in Figure 10 one may conjecture that the

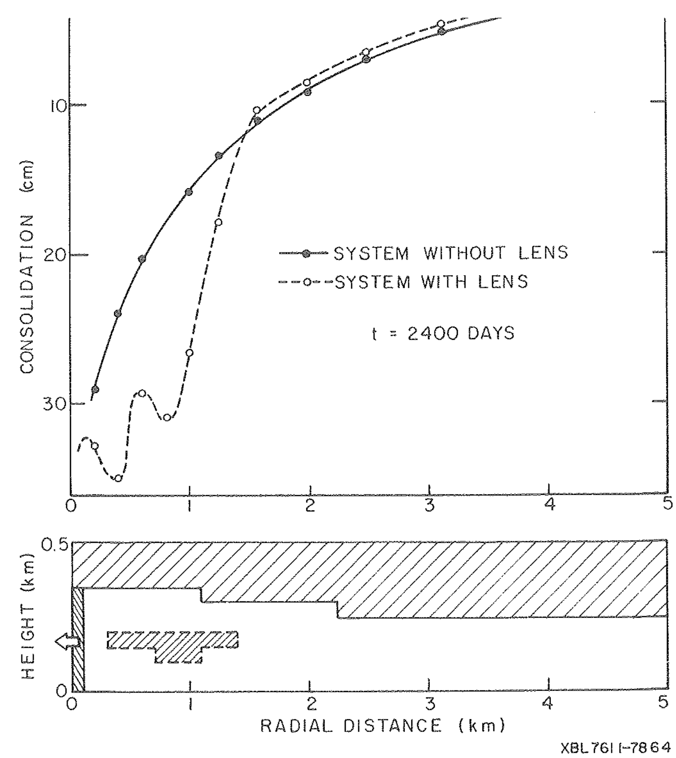

Figure 9. Effect of a heterogeneity on the consolidation profile of the two-layer system.

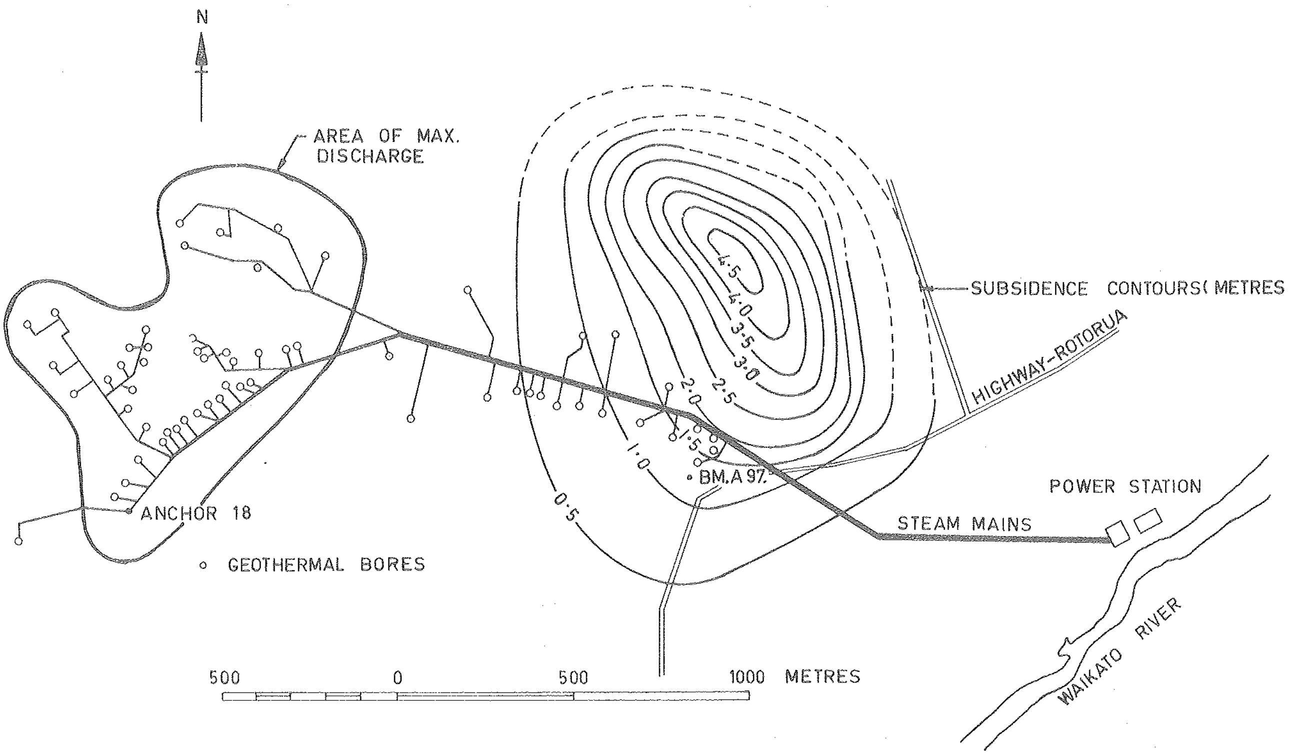

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Figure 10. Total subsidence at Wairakei geothermal field, New Zealand, 1964 to 1974. (From Stilwell et al.[2]).

disposition of the subsidence bowl at Wairakei is related to the presence of a relatively large thickness of highly compressible materials below the region of the subsidence bowl.

The cases studied indicate that in order to realistically simulate the compaction of geothermal systems it is important to consider the temperature (and/or pressure) dependence of rock and fluid properties, especially viscosity. Also, the significant effects of the materials' previous stress history, and of heterogeneities on the deformation behavior of these systems, has been illustrated.

PLANNED ACTIVITIES FOR 1978

1. Program CCC will be applied to simulate the behavior of actual geothermal systems if adequate information becomes available.

2. A dual reservoir-overburden model will be developed to study the propagation of deformations through the overburden in response to displacements induced at the reservoir-overburden interface.[8] This will permit the computation of horizontal as well as vertical ground deformations resulting from reservoir pressure changes.

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UTILIZATION AND CONVERSION TECHNOLOGY

The development of geothermal energy requires accurate economic and technological assessments of developmental projects. Yet the information required to make these assessments is not always available. The LBL program of utilization and conversion technology attempts to provide this information; it is an extension of present technologies into areas that were not of interest previously.

The program is divided into two parts: technology development and utilization projects. In technology development, we are providing analytical tools and data required to fully understand the processes by which geothermal energy can be economically utilized. These tools and data, plus other laboratory resources, are then applied to a number of DOE-sponsored projects that serve as paths to the geothermal industry.

Because the binary-cycle process is expected to be the method chosen to exploit most moderate-temperature hydrothermal resources for electrical energy, most of our technology development projects are focused on this binary process. The Binary Fluid Experiment is providing laboratory-quality data on heat transfer film coefficients of the various candidate hydrocarbon working fluids. Computer code GEOTHM is being developed as a flexible and cost-effective design and analysis tool. The direct-contact heat exchange project is exploring a technique expected to improve the economics of second generation geothermal power plants. The direct-contact/turbine loop tests reported here were actually the first time electricity had been generated in the United States from geothermal energy with the binary-cycle process.

Utilization projects during 1977 included work at DOE's Niland Geothermal Loop Experiment Facility (GLEF) and East Mesa Geothermal Component Test Facility (GCTF). LBL also provided technical review and evaluation assistance to DOE's San Francisco operations office for their direct-use activities.

LBL's activities at the GLEF included data management and reduction and a feasibility study of installing a hydrocarbon turbine at this site. DOE wanted to investigate the desirability of conducting hydrocarbon turbine tests at the GLEF. Therefore, LBL conducted an intensive survey of turbine manufacturers and users, prepared turbine and layout options, and drafted a preliminary test plan. The end recommendation, after consideration of the size of turbine possible at the GLEF, the modifications to the GLEF required, and the responses of turbine manufacturers, was to not perform these turbine tests at the GLEF. This recommendation was presented to DOE in September.

As reported last year, LBL had been assigned responsibility for initial management of the GCTF. During the first nine months of 1977, LBL maintained a resident supervisor at the GCTF to be responsible for the service provided each experimenter.

In April 1977, full scale operations became possible on three shifts seven days a week when ERDA supplied an operating contractor. By that time one test had been completed and two others were well under way. During this period LBL personnel traveled extensively to the GCTF to support testing and make the facility ready to operate at full capacity.

From April through September, service was provided for five additional experiments. All investigators requesting test time had been accommodated and had met their test objectives by the end of September. At the end of September GCTF was routinely operational and LBL's task was complete. Management responsibility was returned to ERDA to be contracted out to industry.

The remainder of the year was devoted to assuring a smooth transition to the contractor.

Six of the eight experimenters for whom support services were provided during the year were from private industry. One of these was privately funded, the other five were funded by ERDA. One university and one national laboratory, both with ERDA funding, operated the remaining two experiments.

1978 will see the work on GEOTHM and the Binary Fluid Experiment continued, along with the GLEF data reduction. Direct-contact heat exchange activities will increase with the construction and initial testing of a 500 kW pilot plant and conceptual studies of commercial-size direct-contact power plants. A very large utilization project, the DOE Geothermal Demonstration Plant, will begin in 1978.

Technology Development

ENERGY CYCLE SYNTHESIS AND CONCEPTUAL DESIGN OPTIMIZATION AT LBL

W. L. Pope, H. S. Pines, L. F. Silvester, M. A. Green, and P. A. Doyle

INTRODUCTION

LBL is developing a general thermodynamic process computer code, GEOTHM.[1-3] Since 1974, this code has been under development through funding from the U.S. Department of Energy, Division of Geothermal Energy (DOE/DGE). Its principal use is for the conceptual design and optimization of geothermal power plants. However, because of its versatility, GEOTHM can be used to design and optimize fossil fuel plants,[4] nuclear and solar plants, ocean thermal gradient plants,[5] and hybrid combinations[4] of the above. Using sophisticated optimization algorithms, GEOTHM is capable of designing and optimizing complete cycles or individual subsystems efficiently for user-specified criteria with up to 55 independent design parameters.

The development of the GEOTHM code is the responsibility of the Cycle Studies Group of the LBL Mechanical Engineering Department. This group is part of a larger engineering team assigned to the LBL Earth Sciences Divison.

A previous annual report[5] discussed the GEOTHM code structure, its special features, and computational algorithms. In this report we discuss rationale for continued code development, recent code improvements, applications, and how this LBL effort complements the overall objectives of DOE/DGE.

GEOTHM code development has been motivated by the following rationale. The technical or economic feasibility of energy conversion systems or the relative ranking of competing plant design alternatives is determined (or biased) by input choices of cycle configurations, thermodynamic states, working fluid selections, site-specific conditions, and economic assumptions.[7] No significant experience base (conventional design practices) is available to draw upon for the selection of economically optimum thermodynamic state conditions in hydrothermal geothermal power cycles. The conventional practices built up as part of the power industry do not apply to the design of Rankine-cycle processes for moderate-temperature geothermal heat sources and new working fluids.

GEOTHM's modular structure, extensive fluid properties repertoire, flexible economic coding, and unique, single-step multiparameter optimization capability, is an ideal tool to establish new design practices for these systems by introducing a minimum of the designer's subjective biases.

For these new complex systems, GEOTHM is the most cost-effective means to reconcile the many, often intuitively conflicting, thermodynamic and cost considerations required to generate optimum total-system designs. Other existing computer codes do not have this overall capability and do not meet the needs of the geothermal industry because they are either proprietary, limited in scope and flexibility, or inefficient.

OBJECTIVES

The primary objective of the Cycle Studies Group is to develop, document, and make available to the geothermal industry a general, cost-effective, thermodynamic cycle simulator for analysis of energy conversion processes and power plant designs.

A secondary objective is to use GEOTHM in-house for general geothermal plant and sub-system design studies.

PLANNED ACTIVITIES FOR 1977

The primary group objective established for 1977 was to document the GEOTHM code with a User's Manual for Passive Mode Design. In addition, a secondary objective planned was to make several code improvements in the areas of expanded fluid properties routines and new process models.

After a brief study for our program manager at DOE,[8] we were asked to submit a proposal to the Centers for the Analysis of Thermal Mechanical Conversion (CATMEC) to do general economic studies on state-of-the-art geothermal energy conversion cycles. (CATMEC is a committee of representatives from universities and national laboratories, headed by Prof. J. Kestin of Brown University, that advises DOE/DGE on establishing new areas of engineering research related to DGE goals.) We soon found that to achieve our primary objective and make a timely contribution with the general studies, the secondary objective, GEOTHM improvements, had to be revised. The originally planned GEOTHM improvements had been to incorporate a new two-phase flow well model process routine, include binary fluid mixture properties including noncondensable gases with appropriately expanded process models, include more detailed design process models (i.e., heat exchangers, condensers, expanders, etc.), and document the optimizer routines.

The revised secondary objectives established for 1977 were to perform General Economic Studies on conventional, state-of-the-art, hydrothermal geothermal energy conversion cycles for resource conditions of near-term exploitability, and code improvements required to complete those studies. Documentation of the optimizer has been deferred to fiscal year 1978.

After the proposed general economic studies had been reviewed by the CATMEC committee, the study scope was limited to the conceptual design of the following conventional, 50 MWe (net) geothermal power cycles:

1. simple binary cycles with single component secondary working fluids and conventional surface heat exchangers and condensers;

2. simple two-stage flashed steam cycles.

The objective established for the general economic studies was to determine the mutual interaction of the energy cost and resources utilization efficiency for conceptual design geothermal power plants, on moderate-temperature resources of near term exploitability, as influenced by the following independent variables: resource temperature ($100^{o}C \le RT \le 300^{o}C$), maximum flow rate per well ($200\ Klb/hr \le WF \le 800\ Klb/hr$), selection of isobutane, isopentane, or propane as secondary working fluid (binary cycle), noncondensable gas content for flashed steam cycle ($0.0 \le \%NCG \le 3.0$), and wet bulb temperature ($50^{o}F \le \overline{TWB} \le 80^{o}F$).

ACCOMPLISHMENTS FOR FISCAL YEAR 1977

Primary Objective

Our primary objective - to document the GEOTHM code with a User's Manual for Passive Mode Design - has been achieved.[9] In addition, LBL sponsored a three-day GEOTHM workshop in July 1977 attended by 25 individuals representing 17 organizations from industry, government, and other national laboratories that are engaged in geothermal research and development.

After a day and a half of introductory lectures by LBL staff in the use of the recently developed interactive version of the GEOTHM code, attendees spent a day and a half solving problems on complete binary and flashed-steam cycles, and heat exchangers using GEOTHM on the LBL 6600/7600 computer via six remote terminals set up in the conference center for the workshop.

The LBL-sponsored workshop was found to be an excellent vehicle for transfer of technology to industry. By January 1978, one third of those organizations that attended the workshop were using the GEOTHM code in their work. (GEOTHM may be accessed via interactive mode by any user from a remote data terminal to the LBL 6600/7600 computer.) In addition, from responses to a detailed questionnaire distributed after the workshop, we obtained a better understanding of the geothermal community's software needs which will enable us to establish future project objectives and priorities.

There was general agreement among workshop attendees that LBL should concentrate on three general areas of code improvement. They are documentation of the GEOTHM optimization routines, expansion of the fluid thermodynamic and transport properties repertoire, and inclusion of more detailed process models, especially direct-contact heat exchangers and condensers.

Secondary Objectives: General Economic Studies

Computations have been completed on the first phase (binary cycles - isobutane) of the Multiparameter Optimization Studies of Geothermal Energy Cycles.[10] Figures 1, 2, and 3 are examples of computer-generated plots of energy cost-resource utilization efficiency versus resource temperature; well flow rate; and wet bulb temperature, respectively, for 50 MWe simple binary cycle power plants. The following conditions have been assumed for all three figures:

a. low salinity "brine" simulated as pure H_2O;
b. working fluid simulated as pure isobutane;
c. turbine efficiency, 85%; generator, 98%; all motors, 95%;
d. all pump efficiencies = 80% except downhole production well pumps, where efficiency = 50%;
e. plant capacity factor, 85%;
f. all direct and indirect plant and field costs normalized to baseline binary cycle at Heber from Reference 11 using the factored estimate method described in Reference 7.

Also, the cycles assume conventional shell-and-tube exchangers and condensers and heat rejection via conventional forced draft wet cooling towers. The production wells are modeled here simply as single-phase, frictionless, adiabatic, vertical pipes with downhole, high speed, multistage centrifugal pumps, shaft driven from the surface. The subsystem capital costs, and the plant and field direct and indirect costs were normalized to architect/engineer (A/E) values.[11] These binary cycle computations, with isobutane as the working fluid, were completed after verifying with the LBL-developed zoned heat exchanger routine, SIZEHX,[12] that the overall heat transfer coefficients assumed by the A/E firm for conventional shell and tube exchangers with the fouling factor model from Reference 13 tests were reasonable.

It can be noted from Figures 1 and 2 that for the binary cycle the energy cost is a strong function of both the resource temperature and the maxi-

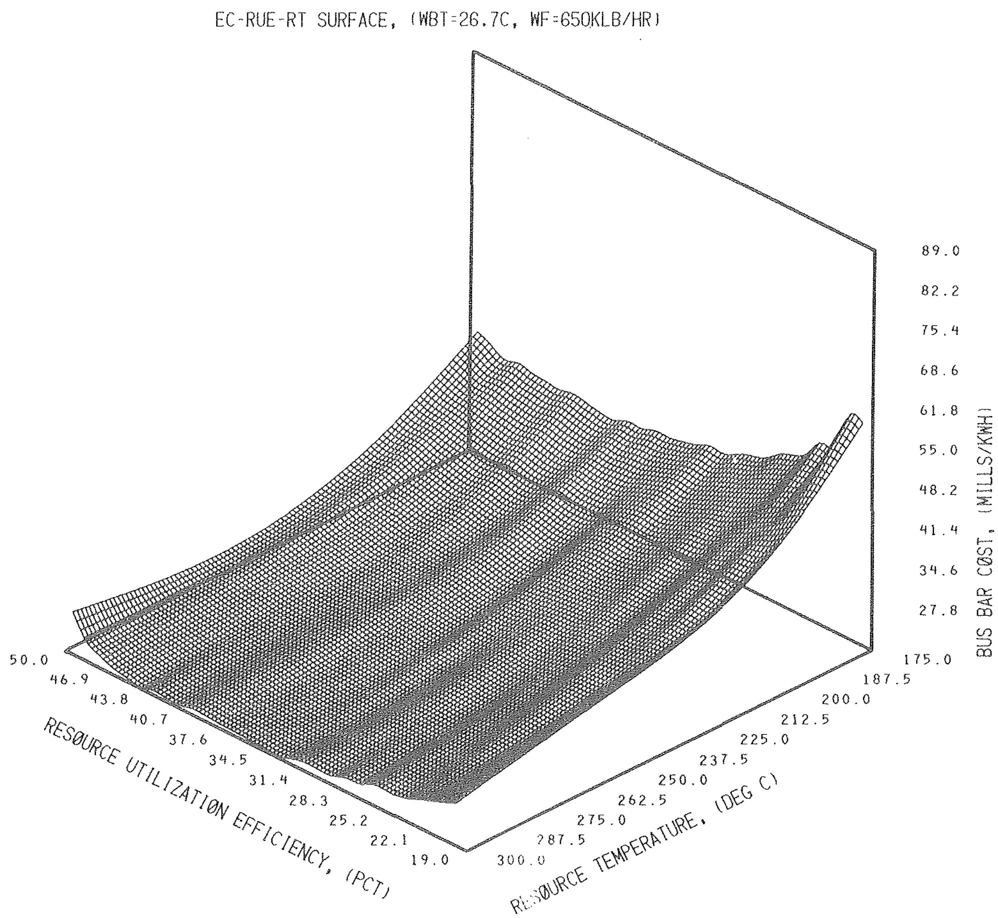

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Figure 1. Energy cost-resource utilization efficiency - resource temperature design surface for 50 MWe (net) binary cycle power plants on moderate temperature, low salinity, hydrothermal resources. Maximum flow rate per production well = 650 Klb/hr; wet bulb temperature = 26.7°C.

mum flow rate per well. Similar behavior is, of course, expected for the flashed steam cycles. Resource utilization efficiencies at the minimum energy cost are in the neighborhood of 30-45 percent, which is significantly lower than previous economic analyses[7] have suggested.

The wet bulb temperature, see Figure 3, also influences the energy cost, but to a lesser degree than either the well flow rate or the resource temperature for the moderate range of wet bulb temperatures considered. However, the seasonal wet bulb temperature swing can be a deciding factor (if it is large enough) in either site selection or process selection (say binary vs flashed steam) for geothermal power plants on moderate temperature, low salinity resources when all other site-specific conditions are considered equal. The lower the resource temperature, the greater the significance of the design wet bulb temperature.

After a binary cycle power plant is built, for example, it is quite possible to generate significantly more net power than its design rating by utilizing what are called "floating cooling" techniques, that is, by continuously adjusting the condensing temperature to track seasonal wet bulb temperature variations. Conversely, for flashed steam cycles, density limitations at the expander exhaust prevent significant condensing pressure changes, thus restricting the net power output to design values. This "floating cooling" concept has been studied extensively for binary cycles by our colleagues at the Idaho National Engineering Laboratory.[14]

Secondary Objectives: GEOTHM Code Improvements

After a temporary suspension of code "improvements" in early 1977 to modify GEOTHM for interactive use and complete the documentation required

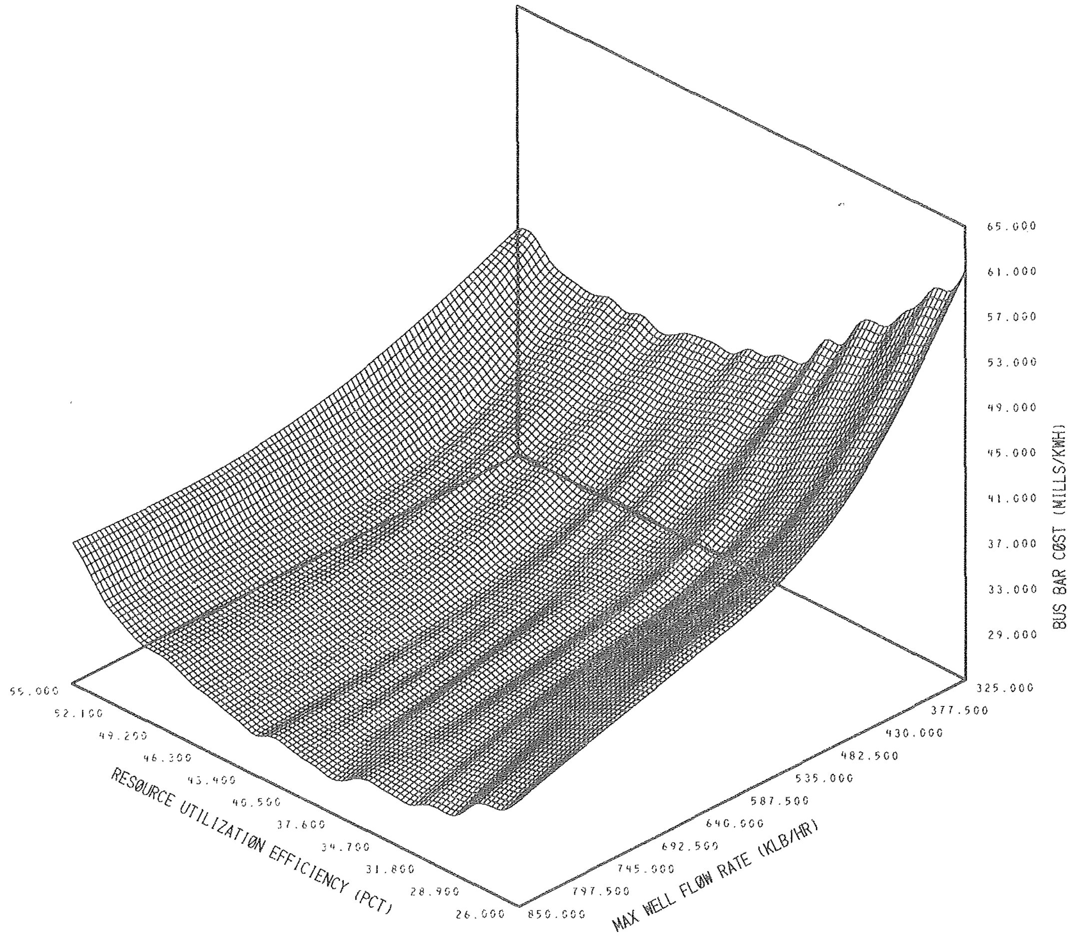

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Figure 2. Energy cost-resource utilization efficiency - (production) well flow rate design surface for 50 MWe (net) binary cycle power plants on a 200°C low salinity hydrothermal resource with a wet bulb temperature of 26.7°C.

for the Workshop, code development continued in the previously-mentioned areas.

Optimization

The existing optimizer routines, based on the computational algorithms discussed elsewhere,[6] have been tested extensively on binary cycles in the general economic studies previously mentioned and with SIZEHX for cost optimizations of heat exchanger subsystems.

In addition, the optimizer has been tested on other cycle subsystems (for example, hydrocarbon expanders) in the design mode. Experience with the complex GEOTHM optimization routines has progressed to the point where we now feel we can confidently schedule a Geothermal Cycle Design Optimization Workshop for late fall.

Fluid Properties Improvements

The following fluid property capabilities were recently added to the in-house version of the GEOTHM code and will later be incorporated in the user version.

Thermodynamic properties:

a) isopentane
b) propane
c) N-pentane
d) N-butane

} from Reference 15

e) supercritical steam, from Reference 16

Transport properties:

a) isobutane
b) isopentane
c) propane

} from Reference 17

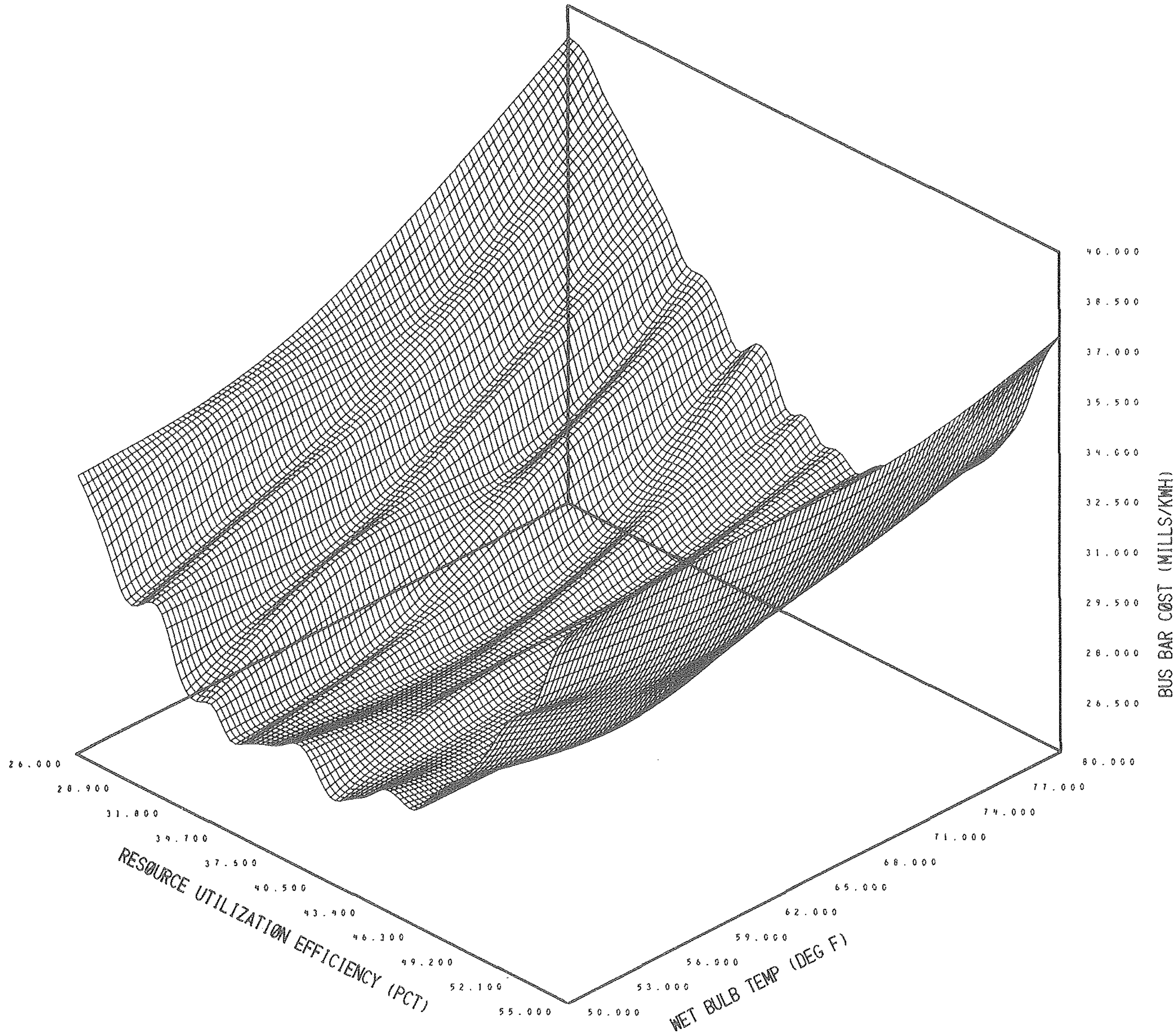

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Figure 3. Energy cost-resource utilization efficiency - wet bulb temperature design surface for 50 MWe (net) binary cycle power plants on a 200°C low salinity hydrothermal resource with maximum production well flow rate of 650 Klb/hr and atmospheric relative humidity = 20%.

Figures 4 and 5 depict the transport properties (thermal conductivity and viscosity, respectively), of isobutane as used in GEOTHM. The sharply rising cliff marks the vapor-liquid saturation curve where the transport properties change abruptly upon changing phases. At temperatures and pressures approaching the critical values, property differences between phases disappear. Consequently the cliff blends smoothly with the concave surface marking the supercritical region. The small bumps atop the cliff and along its foot are artifacts of generating the surface from a discrete set of data points.

In addition to expanding the fluid properties capabilities of GEOTHM, separate programs that compute the thermodynamic and transport properties of binary mixtures of light hydrocarbons were developed, plus a graphics package that allows the results of a GEOTHM computation to be conveniently displayed.

Process Model Improvements

The following process model improvements have been made to the GEOTHM code since the workshop:

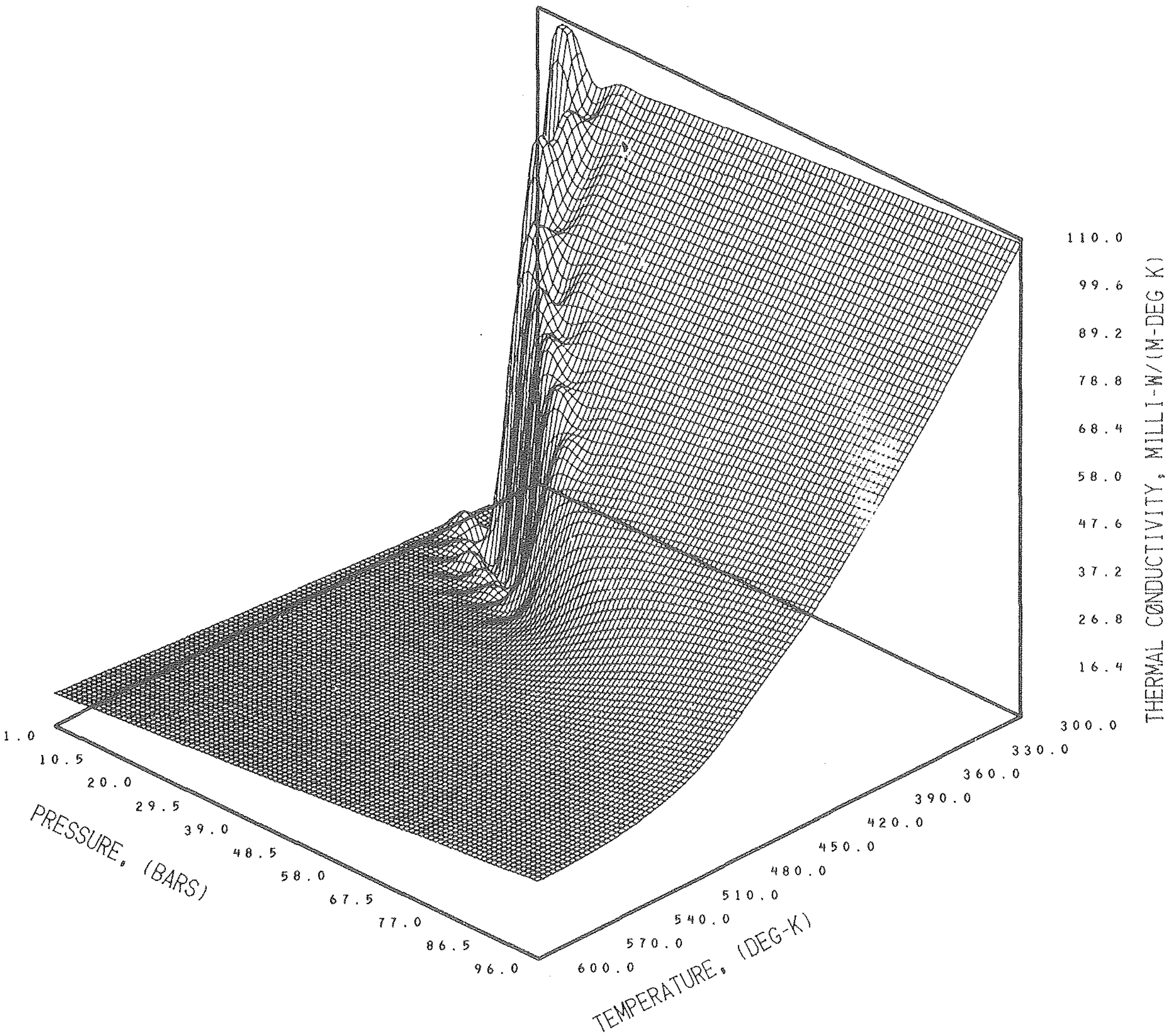

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Figure 4. Thermal conductivity (milli-W)/(m-^{o}K) of isobutane as a function of temperature (^{o}C), and pressure (bars).

The <u>GEOTHM single phase</u> well model is a simplified version (wherein pipe friction is ignored) of a routine developed by Elliott.[18]

The <u>pipe model</u> has added a routine for turbulent flow pressure drop. If one puts in the desired drop along the pipe (this may, in some cycles, be an optimizable parameter), the diameter of the pipe and the heat loss from the pipe are calculated.

A <u>burner routine</u> has been added to GEOTHM. This routine models the combustion of hydrocarbon fuel in air. The burner requires that the air inlet temperature, the exit combustion gas temperature, and fuel characteristics be given. The required fuel characteristics include: the heating value, the hydrogen-to-carbon ratio, and weight percentage of inert substances. The burner calculates the reactive mass flows of the fuel, air, and combustion gas streams. The burner routine required a new subroutine to calculate the properties of hot air and combustion gases. These properties can be calculated with reasonable accuracy for a range of temperatures from 0^{o}C to about 2200^{o}C.

The <u>axial flow expender model</u>. The Barber-Nichols (organic fluid) turbine performance and cost correlations[19] have been incorporated into a new conceptual-level turbine design routine. Overall turbine efficiency may be computed as a function of the specific speed, N_s, and specific diameter, D_s, defined as:

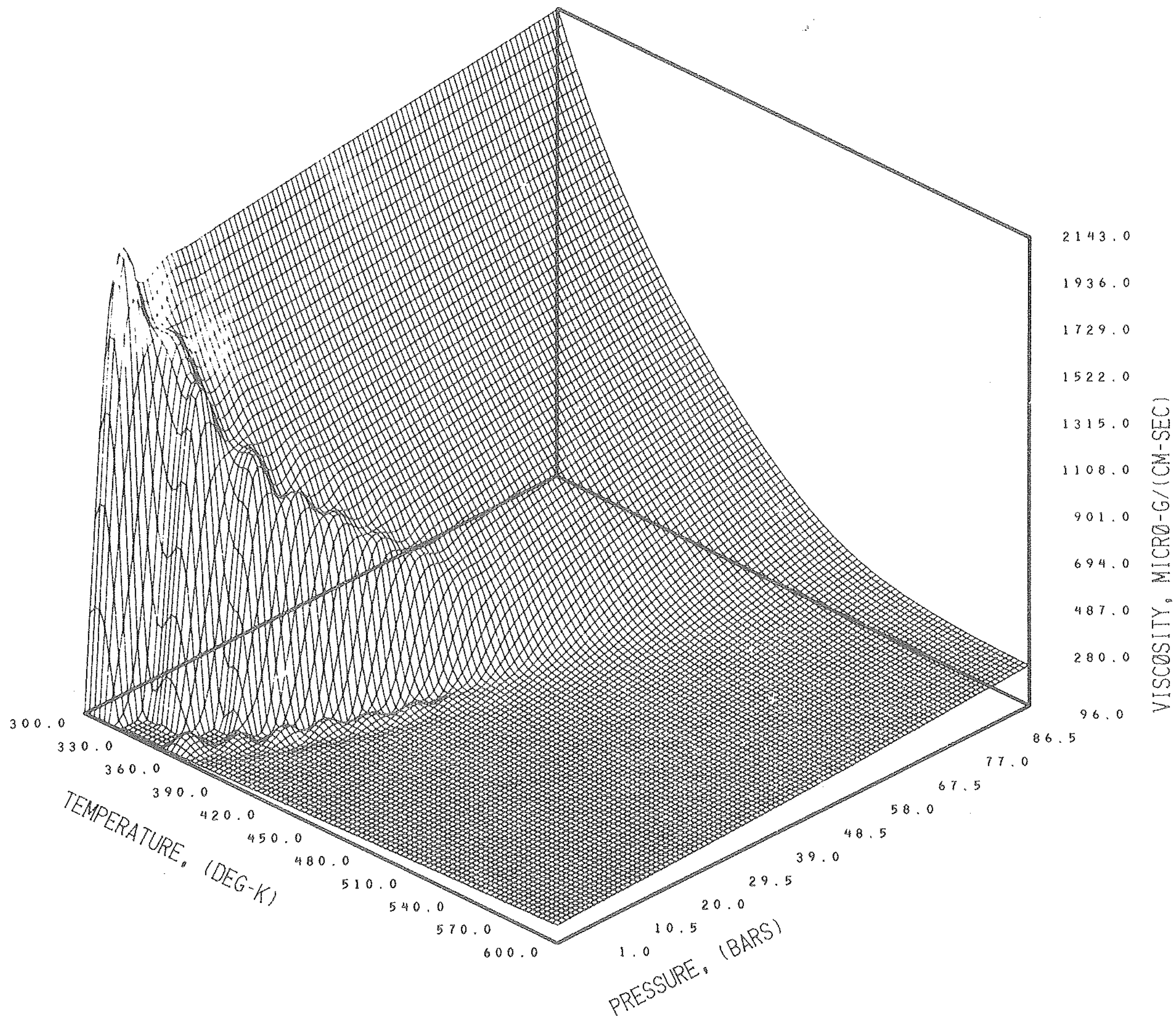

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Figure 5. Viscosity (micro-g)/(m-sec) of isobutane as a function of temperature (^{o}C), and pressure (bars).

$$N_s = \frac{NQ_3^{1/2}}{H_{ad}^{3/4}}$$

$$D_s = \frac{DH_{ad}^{1/4}}{Q_3^{1/2}}$$

N = rotational speed (RPM)

Q_3 = rotor flow rate (ft^3/sec)

H_{ad} = adiabatic head (ft)

D = diameter (ft)

For a fixed load (mass flow and adiabatic head) imposed upon the machine by the power plant, these relationships enable the user to select the turbine size (diameter of the exhaust end) and rotational speed (RPM) as independent design parameters.

These new design relationships can be used in GEOTHM in the following ways: for the Passive Design Mode, GEOTHM computes turbine efficiency and cost as a function of user-dictated turbine size and RPM parameters; and GEOTHM computes turbine size and cost as a function of user-dictated efficiency and RPM parameters. For the Dynamic (Optimization) Design Mode, GEOTHM will design the turbine with size and RPM as optimizable parameters to achieve some optimum user-specified thermodynamic or cost objective. The Dynamic Design Mode application is illustrated by the following example problem. For fixed mass flow and adiabatic head, GEOTHM was instructed to design a turbine to satisfy the objective of maximum efficiency. This is equivalent to determining the unique turbine size and RPM corresponding to the point of maximum efficiency in Figure 6. Figure 7 illustrates that the GEOTHM optimizer converged upon the optimum solution for three radically different first-guesses in the pair of optimizable parameters.

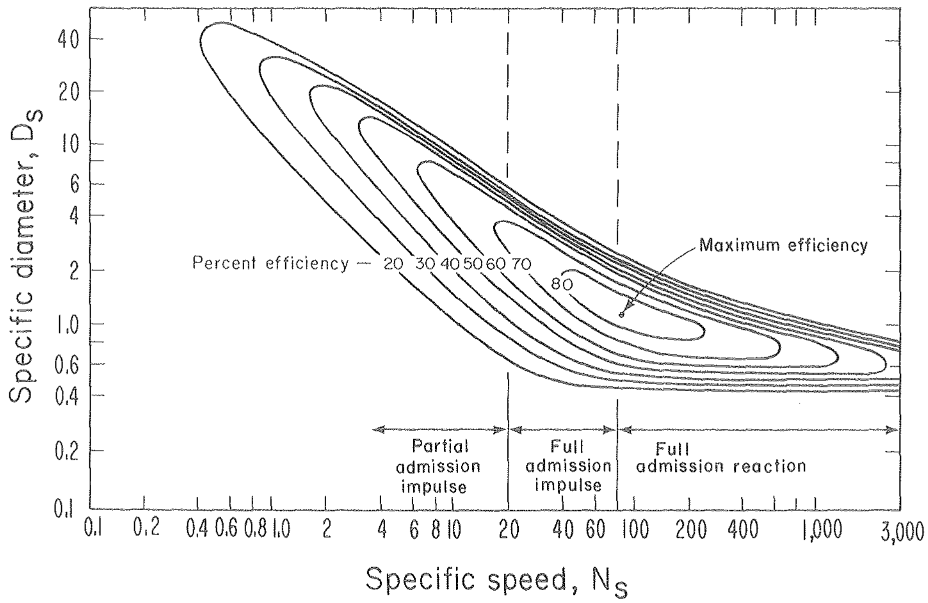

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Figure 6. Design performance chart, axial-flow turbines.

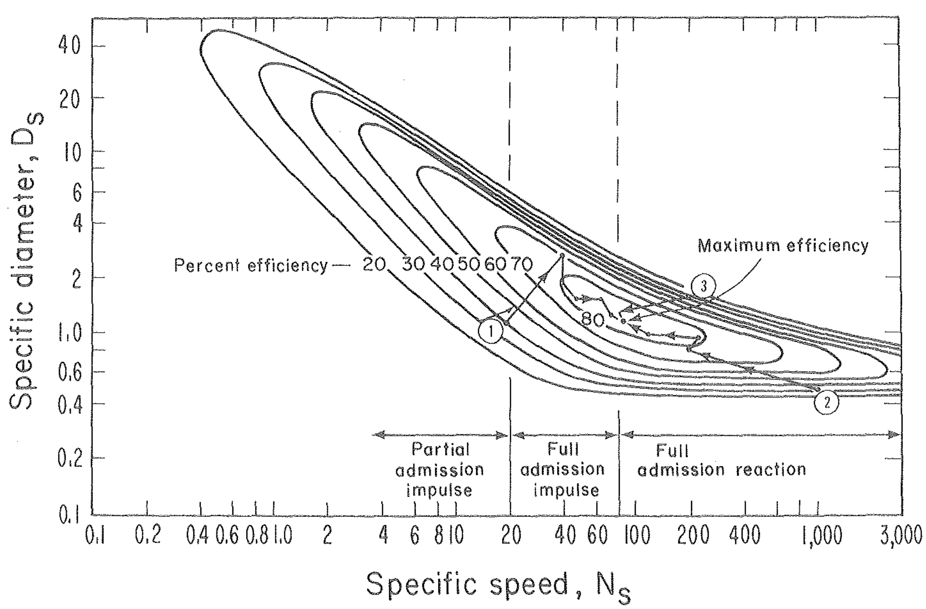

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Figure 7. GEOTHM optimizer converging upon the maximum efficiency turbine design for three different first-guess designs.

When the turbine design is frozen, that is, with fixed size and RPM, GEOTHM can be used to predict turbine performance under Off-Design operating conditions as follows:

a) Passive Off-Design Mode: GEOTHM computes Off-Design turbine efficiency for changing mass flow and adiabatic head through the turbine.
b) Dynamic Off-Design Mode: GEOTHM computes optimum mass flow and adiabatic head conditions to satisfy an optimum user-specified Off-Design objective, for example, maximizing plant net power output as the atmospheric wet bulb temperature varies.

The dynamic Off-Design Mode capability of GEOTHM will be employed to study the floating cooling concept of Off-Design power plant operation.

Other Group Accomplishments in 1977

Three GEOTHM application papers[5,10,20] were presented in 1977 at various energy conferences. The GEOTHM/SIZEHX program package was used to scope the design/procurement of the primary supercritical heaters for the DOE/EPRI Heat Exchanger Test at Heber, California.[21] GEOTHM was used to model the Niland Geothermal Loop Experiment Facility (GLEF) in support of a feasibility study for this Salton Sea facility.[22]

Although LBL had no part in the study, the GEOTHM code was used by a DOE contractor recently in an excellent design study[4] of hybrid geothermal/fossil power plants to meet future electrical demands of the Los Angeles Basin.

ACTIVITIES PLANNED FOR 1978

The following is a list of planned activities. The amount of this work we accomplish could be influenced by mid-term redirection due to changing DOE/industry goals or progress at other laboratories. For example, when currently funded theoretical work on two-phase flow in vertical pipes is completed, this process model could be added to GEOTHM.

I. Code Develoepement

A. Fluid Properties - expand fluid properties routines to consider two-component fluid mixtures, for example, fluid plus a non-condensable gas, light hydrocarbon working fluid mixture, or a mixture of working fluid and brine for cycles with direct contact heat exchangers.

B. Process Models
1) Modify existing process models to treat the two-component fluid mixtures in A above.
2) New process models: direct contact exchanger and condenser routines, and axial flow expander model. Code changes for optimizations of surface heat exchangers, as elements of complete plants.

II. Code Documentation and Technology Transfer

A. User's Manual update including Design Optimization

B. Workshop on optimization of geothermal power plants

III. General Economic Studies

A. Complete binary cycle work described herein.

B. Complete flashed steam cycle studies.

IV. Geothermal Cycle Analysis Support

A. Periodic analyses of contractors' selected design for the first commercial-size hydrothermal demonstration plant[23] (as directed).

B. Synthesis and periodic analysis of a new LBL proposed 500 kW, direct contact, binary cycle geothermal pilot plant.

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INVESTIGATION OF HEAT TRANSFER COEFFICIENTS OF BINARY CYCLE WORKING FLUIDS

B. W. Tleimat and A. D. K. Laird

The objective of the Binary Fluid Experiment (BFE) is to obtain baseline heat transfer data for working fluids being considered for geothermal binary cycle power systems. These data will be used to calculate film coefficients for heating and boiling as well as condensation for uncontaminated working fluids.

In the binary system, geothermal brine is used to heat another, or secondary, fluid steam power plant. Depending on the brine temperature and other conditions, the secondary fluid may be water, ammonia, refrigerants, light hydrocarbons, other fluids or appropriate mixtures of fluids.

Heat transfer equipment, principally to heat and condense the secondary fluid, accounts for approximately half the capital cost of a binary cycle geothermal power plant. That this cost is significant is shown by the cost estimate for a 10 MW experimental power generation facility, prepared jointly by LBL and the Rogers Engineering Company, Inc., of San Francisco. The installed cost of the plant, excluding brine production and injection wells, was expected to be $12 million, of which the heat transfer equipment accounted for $6 million. On the same basis, the heat transfer equipment alone for a 50 MW plant would cost about $30 million. In such cases, an inexact estimate of the heat transfer coefficients can have serious effects. If the coefficients used in the design are too high, the plant may fail to meet its performance guarantee. If too low, the plant will be overdesigned and wasteful.

Despite the importance of heat transfer in binary cycle plants, there is a real shortage of good heat transfer data for isobutane and other candidate secondary fluids. This is especially true for designs where the secondary fluid is in the supercritical region. Computer studies, LBL's GEOTHM for example, indicate that operation in the supercritical region will be the most efficient. Heat transfer coefficients in this region are being experimentally investigated.

The Binary Fluid Experiment has been designed to provide experimental data on heat transfer coefficients of the various candidate secondary fluids. It will establish baseline data on film coefficients for several light hydrocarbons and mixtures of light hydrocarbons, refrigerants and mixtures of refrigerants, and ammonia. Data will be gathered from the BFE for the ranges of heating and condensing temperatures that would be expected for geothermal power plant applications.

The Department of Energy (DOE) is sponsoring several programs to obtain data on brine-side heat transfer coefficients which are subject to degradation from corrosion and scaling. Good baseline data for the secondary-fluid side will show how much overall heat transfer rate degeradation in early binary cycle plants is due to brine-side problems.

A fundamental question in present preliminary binary cycle plant designs concerns the inclusion of a secondary-fluid/secondary-fluid heat exchanger (regenerator or economizer). Precise data on heat transfer coefficients for cooling the secondary-fluid vapor will help plant designers settle the question of the regenerator. These data will be gathered early in the experimental program.

The effects of secondary-fluid contaminants is another area in which design data are lacking. Direct contact between heating fluid and cooling fluid, as in the proposed direct-contact brine to secondary-fluid heat exchangers, will introduce water and probably noncondensable gases, such as carbon dioxide and hydrogen sulfide, into the secondary fluid. Some of this water will be dissolved and some will be entrained. It will be necessary to determine the effects of water on the other heat transfer equipment in order to specify the amount of water that can be tolerated economically.

In addition, it is reasonably certain that the secondary fluid will either contaminate or be contaminated by turbine and pump lubricants. The effects of this contamination on heat transfer are to be measured. Information will also be collected on the deterioration of lubricants contaminated by the secondary fluids.

EXPERIMENTAL LOOP

The BFE is located at the University's Richmond Field Station. The experimental equipment consists of a stainless steel loop simulating a binary system with steam as the heating fluid and a throttling valve instead of the turbine. The loop consists of a heater, surface desuperheater, direct contact desuperheater, condenser, booster pump, a high pressure positive displacement pump and associated valving and control elements and instruments.

Figure 1 is a schematic flow diagram for the BFE. The pressurized secondary fluid is heated inside a single tube with steam condensing on the outside of the tube. After heating, the secondary fluid expands through a throttling valve and is introduced into a direct contact or a surface desuperheater by means of two three-way valves. After being desuperheated, the vapor enters the condenser, condenses on the outside of a single tube identical to that in the heater but containing cooling water inside. The condensed secondary fluid is collected in the secondary fluid hotwell and enters the booster pump where it is slightly pressurized before entering the high pressure pump. During operation with the direct contact desuperheater, the two three-way valves are diverted so that the secondary fluid enters the direct contact desuperheater and the separated vapor goes from this desuperheater to the condenser. Also during this mode of operation a portion of the secondary fluid stream from the booster pump is diverted to the desuperheater and the excess fluid at the bottom is returned to the suction side of the booster pump.

The two tubes in the heater and condenser are made from a 31.8 mm (1.25 in. o.d.) and 19.1 mm (3.4 in. i.d.) type 316 stainless steel tube. The tube was cut into two pieces and honed to an inside diameter of 19.2 mm. In order to obtain uniform wall thickness, the two pieces were machined to an outside diameter of 30.2 mm. The concentricity was then checked by ultrasonic measurement of the tube wall thickness at preset locations along the axis. At each location, the wall thickness was measured at four points 90° apart. These measurements were used to indicate the precise locations of thermocouples imbedded in the wall of the tubes.

Figure 2 shows the location of the imbedded thermocouples in the tube at 5 stations 24 inches apart. By measuring the temperature at these locations, one can determine the inside and outside surface temperatures of the tube regardless of the thermal conductivity of the material constructing the tube. Thus, if one can determine the heat rate between the stations, and measure the vapor temperature outside the tube and the bulk temperature of the fluid inside the tube at the five stations, one can calculate the average inside and outside film coefficient of the four sections. Also by determining the heat rate in each section

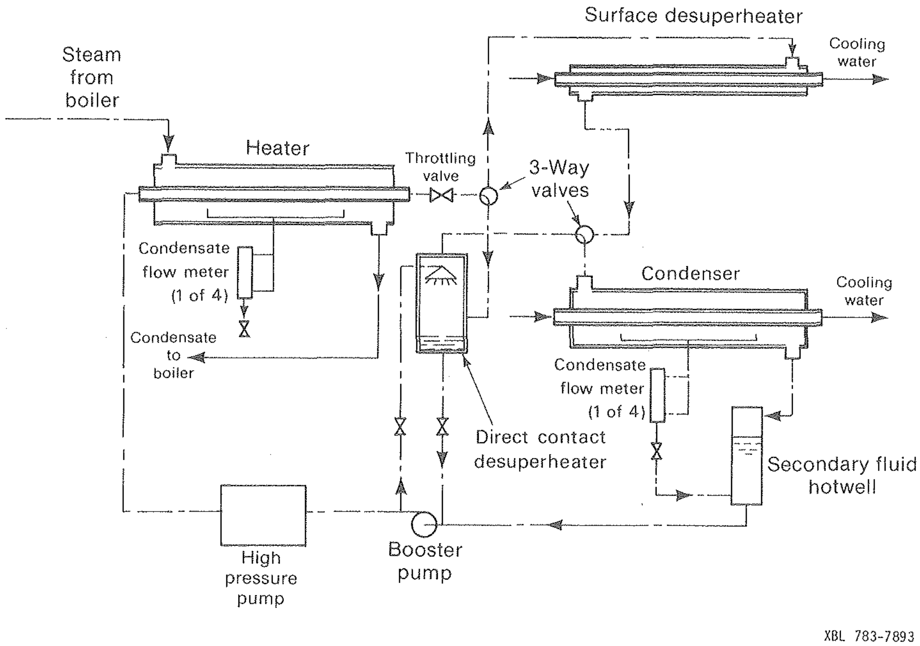

Figure 1. Schematic flow diagram of the Binary Fluid Experiment.

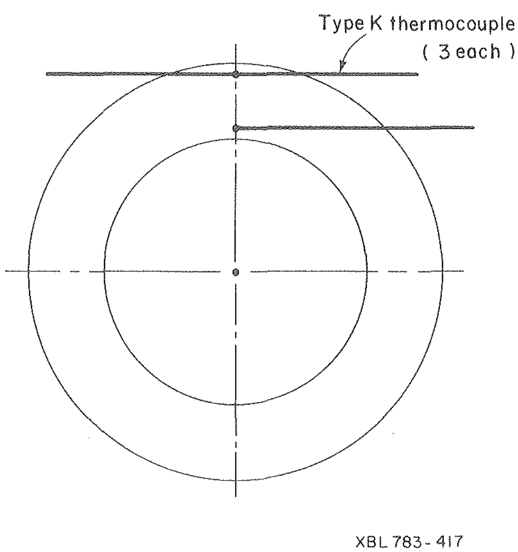

Figure 2. Tube cross section showing location of thermocouples.

and measuring the bulk temperature at the stations, one can determine the state of the fluid inside the tube between the stations.

The rate of heat input to the secondary fluid in the heater and that in the condenser is determined by measuring the rate of condensing vapor on the outside of the tubes at the four sections. This is done by placing a four-section pan under the tube with the sections located under the thermocouples. The condensate formed on the outside of the tube drips into the separate sections of the pan and drains into four vapor-traced condensate flow meters. The condensate flow meter, specially designed for this experiment, is calibrated and has a timer that is operated by photocells to detect rising condensate surface between two predetermined levels. The temperature of the condensing vapor outside the tube is measured by means of calibrated platinum resistance temperature detectors (RTD) and thermocouples located in the vapor space. The pressure in the vapor space is measured by means of calibrated pressure transducers. This pressure measurement is used as a check on the temperature of the vapor and also to detect the presence of noncondensable gases in the vapor space. The bulk temperature of the secondary fluid in the heater is measured by a traveling platinum RTD inside the tube. However, in both heater and condenser, the bulk temperatures of the secondary fluid and cooling water at both inlet and outlet are measured by platinum RTD's.

The experimental equipment was designed, built and pressure-tested by January 1977. Shakedown tests were made with water on plain tubes in the heater and condenser. Modifications were made to both booster and high pressure pumps to assure leakproof operation; also, the seals between the steam and secondary fluid were modified to assure the absence of contamination to the working fluid. Several pressure and pressure difference transducers were found unsatisfactory and returned to vendors for replacements. After these runs, the system was drained of the water and, during this time, the instruments were recalibrated. The loop was then filled with isobutane and tested for leaks. Several runs were made to establish the experimental procedure as well as to "debug" the control and instrumentation systems. During these runs, preliminary data were obtained on heating and condensation of isobutane. Overall heat transfer coefficients were calculated from the preliminary data. The overall heat transfer coefficient for heating the isobutane ranged from 50 to 200 Btu/hr ft^2°F. The overall heat transfer coefficient for isobutane condensing on the outside of the tube ranged from 50 to 120 Btu/hr-ft^2°F.

The loop was shut down at the end of September 1977 for installing the instrumented tubes as well as for installing throttling valves and isobutane heater to extend the range over which accurate data can be taken. The instrumented tubes were installed with their associated thermocouples at the end of December 1977.

TEST OF A GEOTHERMAL POWER CYCLE INCORPORATING A DIRECT-CONTACT HEAT EXCHANGER

R. L. Fulton

INTRODUCTION

In the direct contact heat exchange concept (DCHE) as applied to the utilization of geothermal energy, heat is transferred from the geothermal brine to a working fluid by the direct mixing of the two fluid streams. Practiced in the chemical process industry for both mass- and heat-transfer, DCHE holds the promise of more efficient heat exchange, lower cost equipment, and a way to avoid scale deposits on heat transfer surfaces.

The geothermal direct contact heat exchanger (DCHX) is basically a vertical vessel in which the hot brine is introduced near the top and, after being cooled by mixing with the working fluid, leaves at the bottom of the vessel; the cooler working fluid, on the other hand, enters the vessel near the bottom and, as it is heated and vaporized, leaves from the top. The vessel is designed to allow separation of the two fluids at the top and bottom. The successful application of DCHE requires that the two fluids be relatively insoluble, and that they have different densities. The insolubility requirement reduces the amount of one fluid dissolved in the exiting stream of the other, and the density difference allows the relative flow up and down and the separation of the streams at the top and bottom of the vessel.

Working fluids considered for use in geothermal energy conversion by closed Rankine-cycle processes are also good candidates for DCHE, as they meet the above criteria. Light hydrocarbons (isobutane, pentane, etc.) have received the most attention as working fluids and they exhibit very low solubility in water. In addition, as the level of dissolved solids in the geothermal brine increases, the hydrocarbon solubilities are further reduced.

Since 1975, a number of DOE contractors have conducted design studies and field tests of the DCHE concept. Occidental Research, DSS Engineers, and the University of Utah have all operated DCHX in the field to obtain performance data. In November 1976, LBL began to plan a field test of a complete electric-power generation loop using a DCHX. Barber-Nichols Engineering was selected as prime contractor to provide the turbine/generator unit and to conduct the tests at DOE's Geothermal Component Test Facility (GCTF), East Mesa, California. A schematic of the complete turbine/DCHX test loop is shown in Figure 1. Barber-Nichols then subcontracted to DSS Engineers to provide and operate the DCHX test loop on which DSS was completing tests at the East Mesa geothermal facility.

TEST OBJECTIVES

While the DSS Engineers tests had focused on the DCHX itself, the objectives of the LBL tests were to operate the DCHX with a turbine for 500 hours and to identify and evaluate the problems in a DCHE Rankine-cycle process.

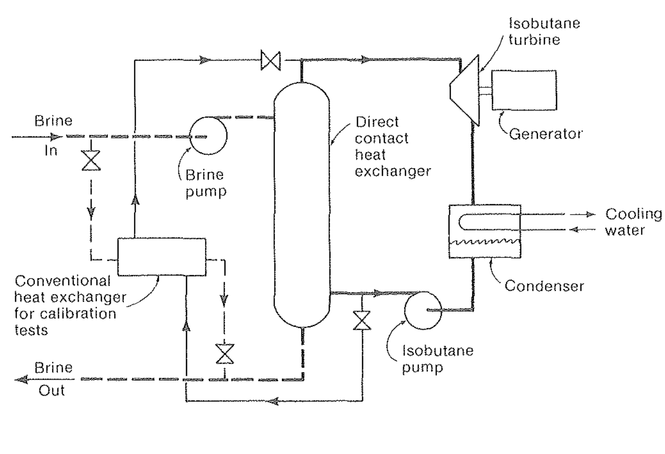

Figure 1. Schematic of turbine DCHX test loop.

Barber-Nichols designed and fabricated a single-stage, partial-admission, axial-flow turbine for an isobutane working fluid. Initial plans called for operating the turbine/generator both with the DSS Engineers DCHX in a subcritical cycle and with the Occidental Research DCHX in a supercritical cycle. The turbine/generator was designed with a set of inlet nozzles for each condition. To date, only the subcritical DCHE cycle has been run, although the turbine has been calibrated at both operating conditions. The two sets of turbine conditions are shown in Table 1.

The heated and vaporized fluid stream flowing to the turbine from a DCHX is a mixture of working-fluid vapor and saturated steam. The percentage of steam varies with the system temperature and pressure. An objective of the tests was to evaluate the effect of this saturated steam on the turbine performance. Predictions of the turbine performance (Figure 2) were made.

Table 1. Turbine operating conditions.

	Subcritical	Supercritical
Isobutane flow rate, lb/hr	2650	2000
Water vapor flow, lb/hr	32	49
Combined flow rate, lb/hr	2682	2049
Max. total pressure, psia	315	600
Max. temperature, °F	220	300
Condensing temp., °F	110	110
Total condensing pressure, psia	83.2	83.2
Turbine available energy, Btu/lb	24.0	35.0

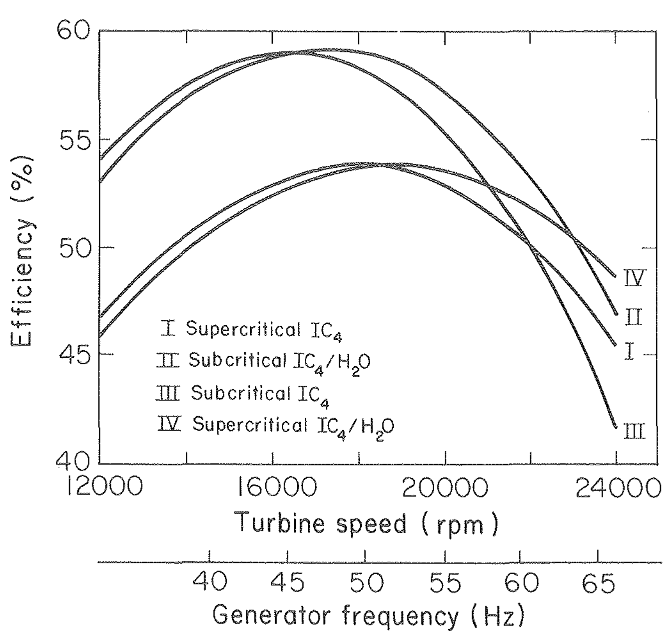

Figure 2. Predicted turbine efficiency.

TEST OPERATIONS

In July 1977, the turbine/generator, electrical load, and control system were delivered to the GCTF and connected to the DSS Engineers DCHX test unit. A conventional surface-type heat exchanger (Figure 1) was also added in parallel to the DCHX for calibration tests of the turbine on pure isobutane.

Subcritical and supercritical calibration runs were made with pure isobutane and subcritical performance runs were made with the DCHX. The 500-hour test of the turbine/DCHX loop was begun on July 26 and ended on August 24. The calibration tests were then rerun.

The Barber-Nichols turbine/generator and other equipment had been designed with a 500-hour test in mind. The DSS Engineers DCHX loop had been designed for a series of short heat transfer tests not lasting more than a few hours each. As a result, most of the mechanical difficulties during the 500 hours of operation were with the brine and isobutane pumps and flow systems. However, the turbine shaft seal did fail at 340 hours, requiring a shutdown and installation of a new seal.

TEST RESULTS

Inspection of the turbine during the seal replacement and after the 500 hours found significant amounts of scale formed in the turbine-inlet nozzles, the turbine housing around the shaft seal, and on the turbine wheel. The scale build-up in the turbine caused a gradual reduction in the turbine efficiency of approximately 20% over the 500 hours of operation. The turbine scale is attributed to liquid-brine droplets carried over with the steam and isobutane vapor mixture from the DCHX. Analysis of the scale found in the turbine showed silicate to be the primary constituent.

The DCHX was also inspected after the 500 hours and a small amount of iron oxide scale was found near the top of the vessel. Neither the amount of scale or corrosion, however, was significant.

Turbine efficiencies during the field tests never quite reached predicted values. One reason was that the isobutane condenser tubes were badly fouled and the design condensing pressure was never reached. However, after correcting the predicted efficiencies for the reduced pressure ratios incurred, the actual performance was still below the predicted performance.

Liquid isobutane droplets in the flow stream to the turbine were most likely the cause of the reduced performance. Two indications of this were that the turbine performance increased more than expected with increased inlet superheat (probably drying the incoming vapor), and that the nozzle coefficients with isobutane were calculated to be much higher than measured with compressed air. The effect of isobutane droplets was seen in both the tests with the DCHX and the tests with the conventional heat exchanger.

The loss of working fluid in the exiting brine stream could be a significant power plant operating cost. Samples of the leaving brine were taken at regular intervals during the 500 hours. During the latter half of the run, after considerable improvment had been made in operating procedures and system stability, the working fluid losses averaged 87 ppm isobutane in the brine. This amounts to 25% of equilibrium solubility with the East Mesa brine.

CONCLUSIONS

The objective of operating the turbine/DCHX loop for 500 hours was achieved. The turbine/generator, electrical load, and load control performed without problem except for the shaft-seal failure. Problems in the brine and isobutane flow systems can be traced to the fact that these subsystems were not originally designed with this type of use in mind.

Working fluid losses were less than equilibrium levels as expected. This non-equilibrium situation comes from the short residence time required for heat transfer in the DCHX vessel. A much longer time is required for equilibrium mass transfer.

The major problems identified were the turbine scaling and low efficiency. It is expected that both these problems can be eliminated by providing adequate mist eliminators and a knock-out drum between the DCHX and the turbine inlet.

FUTURE PLANS

Preparations are being made for another short test incorporating a knock-out drum and better vapor-flow measuring instrumentation. This is expected to increase the turbine efficiencies and reduce the turbine scaling, and to provide more accurate turbine flow data.

DSS Engineers are presently operating the DCHX loop to test techniques for further reducing the levels of working fluid in the exit brine stream.

LBL has begun a project to design and operate a 500 kW DCHE pilot plant in a series of baseline performance tests at the GCTF in 1978.

Utilization Projects

DATA HANDLING FOR THE NILAND GEOTHERMAL LOOP EXPERIMENTAL FACILITY (GLEF)

R. L. Fulton, F. X. Catalan, B. S. Levine, D. W. Merrill, and S. Mitina

INTRODUCTION

In June 1976 the Geothermal Loop Experimental Facility (GLEF) located at Niland in Imperial County, California, began operation as a project jointly funded by the San Diego Gas and Electric Company (SDG&E) and DOE. This facility taps hot geothermal brine from the Salton Sea KGRA through two production wells, for utilization in a four-stage flash-binary loop. Waste fluid from the facility is reinjected to the reservoir through one or two injection wells. The tests have the dual objectives of:

1. Determining the technical and economic feasibility of using fluid from the high-temperature, high-salinity Salton Sea KGRA in a heat exchange train, in order to provide basic information for the design, construction, and initial operation of hydrothermal - geothermal power plants. (Salinities as high as 250,000 ppm total dissolved solids have been measured on this resource, constituting a major consideration in plant design and equipment performance evaluation.)

2. Gaining additional information on the extent and characteristics of the reservoir.

The facility is the first of its kind in the United States and represents more than five years of exploration, research, and development in the Imperial Valley by SDG&E, which also owns, manages, and operates the GLEF. It is intended as a preliminary model to a possible future 50 MW demonstration plant that will use isobutane as the binary fluid.

To accomplish the first of the two objectives outlined above, a Detailed Test Program was developed by the Bechtel Corporation under contract with and submitted to SDG&E in the early fall of 1976. Implementation of this program requires the continuous monitoring of approximately 200 variables, namely, pressures, temperatures, flow rates, and chemical element concentrations, at various points throughout the facility. An instrumentation and data acquisition system designed by the Electronics Engineering Department of the Lawrence Livermore Laboratory provides for analog-to-digital conversion and hourly recordings of the data on cassette tapes by means of a Doric Digitrend Model 220 Data Logger. (This system is covered in LLL's Annual Report.) In addition to automatic recording of most, manual recording of some of the data is also performed.

This note summarizes the activity of the Geothermal Energy Group of LBL's Earth Sciences Division in the handling and reduction of data associated with the first of the two test objectives referred to above. (The implementation of the second objective is part of the Lawrence Livermore

Laboratory Geothermal reservoir engineering effort and is covered in LLL's Annual Report.)

COMBINED EFFORT OF THE GEOTHERMAL ENERGY GROUP AND OF THE COMPUTER SCIENCES AND APPLIED MATHEMATICS DEPARTMENT

The responsibility of LBL's Geothermal Energy Group for data handling and reduction was defined to begin after the data is recorded by the Data Logger and to comprise the following separately identifiable activities:

I. Implementing a reliable method for transmitting the raw data from the Niland test site to LBL.

II. Developing computer programs to screen the raw data for validity.

III. Storing validated data on a routine basis for subsequent reduction and use in the engineering analysis of the test results.

IV. Developing programs for data reduction and engineering analysis according to algorithms outlined in Bechtel's Detailed Test Program and for retrieval of raw and reduced data in tabular and graphic form.

The Bechtel Test Program includes such essential work as:

- Recording plant operation data under both steady-state and transient conditions;
- Calculating heat- and mass-balances and heat transfer coefficients;
- Evaluating steam scrubber performance;
- Calculating boiling point elevation.

This is implemented through a comprehensive test schedule consisting of eighteen specific tasks, starting with water as working ("Binary") fluid, to be changed to isobutane approximately halfway through the test program. These eighteen tasks give rise to as many different computer programming tasks of varying degrees of complexity.

In the latter part of 1976, the Geothermal Energy Group arranged to retain LBL's Computer Sciences and Applied Mathematics Department (CSAM) to address those problems that would require more specialized software and intimate knowledge of LBL's computer system than were available to the Geothermal Energy Group, and it also assigned an engineer on a full-time basis to develop the programs for data reduction and engineering analysis. Since then, CSAM has been providing the expertise to carry out activities I, II, III, and some parts of IV, while the Geothermal Energy Group has been responsible for most of IV and for overall coordination. This has resulted in a mutually rewarding working relationship between the Geothermal Group and CSAM.

ACCOMPLISHMENTS DURING CALENDAR YEAR 1977

The joint Geothermal Group and CSAM data handling effort began in November 1976 and progress during 1977 in the four areas outlined above was as follows:

1. A reliable method for transmitting the raw data from the Niland Test site to storage media at LBL's Computer Center was implemented and has been in operation since June 1977. It consists of physical transport of tape cassettes from the Data Logger at the GLEF site to LBL, conversion by CSAM's Real Time Systems Group to 9-track magnetic tape, and processing of the latter by CSAM's Applications Programming Group. Cassettes are mailed along with hand-logged data to LBL. Hand-logged data is keypunched and stored to be subsequently retrieved along with data logger data.

Although other possibilities were considered, notably direct telephone transmission of the data from the Data Logger to LBL's Computer Center, it was concluded that speed of turnaround was not a critical enough requirement to warrant the added investment in telephone contact charges and in the development of the special error-checking software that this alternative would have required.

2. Computer processing to screen the raw data for validity and to reformat them for subsequent use in engineering computations is essentially in final form. In particuar, since a number of the variables being recorded by the Data Logger (notably flow rates) are subject to wide fluctuations, the Data Logger has been reprogrammed at the recommendation of LLL's Electronic Engineering Department, to perform sub-interval scan readings for the variables so handled. As of this writing, testing of this program on a production basis will proceed once a data cassette incorporating the sub-interval scan feature is received from the facility.

3. Data storage on a routine basis, using a combination of data cell, mass storage, and magnetic tapes has been implemented. The data, upon conversion by the Real Time Systems Group to 9-track magnetic tape, is processed by one of CSAM's technicians to remove noise and other extraneous characters and otherwise make it acceptable to other programs for reformatting and reduction. This noise-filtering and cleanup operation is a crucial and painstaking one. It is to some extent facilitated by the use of the powerful interactive editor NETED, but is not by its nature amenable to full automation because a great deal of non-programmable human judgment is required. The data thus preprocessed is subsequently complemented by inclusion of the hand-logged data, and reformatted into tables that give the plant test history by stream (that is, steam and condensate, working fluid, or cooling fluid), stage, and instrument, in a convenient, highly readable format. Along with these tables, time plots of each one of the measured variables are generated by means of CSAM's Graphics Software. These plots aid the interpretation of test results for engineering assessment purposes. For example, they enable the correlation of fluctuations in the values of associated variables, and resolution of questions such as whether a given instrument is properly functioning or not.

4. The system of data reduction, engineering analysis, and retrieval programs is estimated to be about 60% complete. These programs range from simple displays of test conditions and results to complex engineering computations. For the latter, extensive use is made of the GEOTHM system of programs, developed by other members of the Geothermal Group, to compute the thermodynamic and transport properties of the various fluids.

Work under this activity has also included, in addition to programming, the conceptual development of some of the computational procedures, often given in Bechtel's Detailed Test Program in outline form, into complete, self-contained program specifications. This has been the case, for example, with the programs to calculate heat transfer coefficients for the heat exchangers. It should also be pointed out here that substantial changes in computer program design will be required by the possible adoption of three different procedures aimed at improving the quality of the data, namely:

(a) The performance, within the Data Logger sequence, of sub-interval scans (SIS's) on selected variables found subject to wide fluctuations (for example, surging flow rates), and the averaging of the values so obtained to arrive at a more representative magnitude;

(b) The replacement during computer processing, of questionable Data Logger data by hand-logged data;

(c) The substitution of so-called "indirectly measured values" (IMV's) for some of the values recorded by the Data Logger but lacking in reliability, when this situation has not been resolved by a combination of (a) and (b). An IMV is calculated from related measurements in the system (such as, for example, by heat- and/or mass-balances on individual pieces of equipment or groups of the same). Bechtel has found IMV's to be more consistent and to yield more meaningful data than some of the directly measured data points, and therefore has recommended that IMV's be used in some of the engineering calculations. As of this writing, Bechtel's recommendations are under review by SDG&E.

ACTIVITIES PLANNED FOR CALENDAR YEAR 1978

Test results obtained from the facility so far are under review by SDG&E and the other private and public parties involved in the project, including other groups at LBL and LLL, and it is possible that the Test Program might be modified to include alternative cycles. This would, however, have no effect on the commitment of the Geothermal Energy Group, who will continue to coordinate data handling for the facility, working closely with LBL's CSAM, and with SDG&E and Bechtel. In particular it is expected that:

1. Actual test data from the facility will start to include sub-interval scans of selected variables, which will enable production testing of the computer programs developed to smooth out the values of those variables.

2. Approval by SDG&E of the algorithms to obtain indirect measured values of variables not reliably measurable will be forthcoming, so that the necessary re-programming can be completed.

3. Specifications for the types of selective data retrieval that may still be desirable for better engineering assessment of test results will be finalized, and additional programming developed for this purpose.

DIRECT-HEAT UTILIZATION OF LOW-TO-MODERATE TEMPERATURE GEOTHERMAL FLUIDS

J. Davey

The Direct-Heat Utilization Program for 1977 had two basic functions, to conduct a public awareness survey in the direct-heat utilization area and to provide technical support for others.

SURVEY

Direct-heat utilization is of particular interest because of the abundance of low-to-moderate temperature (to 200°C), liquid-dominated, geothermal resources as compared to the resources feasible for electrical generation. The public awareness survey offered an opportunity to serve a threefold purpose:

1. Present a basic introductory program on geothermal energy and its role in direct heat applications. It also gave the opportunity to "take the pulse" of the private industrial sector, of their knowledge or enthusiasm in evaluating geothermal energy as an alternate energy source for their process.

2. Introduce the Department of Energy (DOE) East Mesa Geothermal Component Test Facility in the Imperial Valley. This facility was established by DOE specifically to assist the rapid commercialization of geothermal energy.

3. Outline the LBL Assistance Programs in the Earth Sciences, the National Geothermal Information Resource (GRID), and the Technology Utilization Program.

The survey included a review of current geothermal reports, and contact with several private and public agencies to achieve the broadest coverage and target the heat intensive industries.

A 35 mm slide presentation was assembled to present the direct-heat use program. The survey lasted four months, was conducted in the western states, and included personal contact with over 75 individuals in the following industries: food processing, chemicals, paper/wood pulp processing, food machinery, horticulture, and dairy. In early 1977 the survey was completed, the data assembled, and a report entitled "Survey Report: Study of Information/Education Discussions with Private Industries and Public Institutions on the Direct Heat Utilization of Geothermal Energy" (Lawrence Berkeley Laboratory report LBL-5988) was published.

The survey clearly indicated the important needs for stimulating the use of this valuable resource, including an intense basic promotional/information program, and an operating demonstration project to prove feasibility and assure the private sector about the potential of direct-heat uses of geothermal energy.

TECHNICAL SUPPORT

In April-May 1977, the Department of Energy's San Francisco Operations office (DOE/SAN) asked LBL for technical assistance in evaluating and commenting on nine contracts awarded in response to their program research and development announcement (PRDA) DGE-76-1. The primary interests of this PRDA was for studies covering a detailed analysis of engineering, economic, and institutional factors associated with either single-purpose or multiple-usage geothermal heat in four industry sectors: industrial processing, agribusiness, commercial building complexes, and residential developments. Proposals were grouped into two main categories: (1) Reservoir Specific Study proposals involved analysis of a specific geothermal reservoir for either a single-purpose or multiple-use application, and (2) Functional Application Study proposals. The nine contracts managed by DOE/SAN consisted of three in the multi-use category, with the balance in the single-use process area. The contract completion dates range from the last quarter of 1977 through the first quarter of 1978.

In mid-1977, DOE issued PRDA-DGE/SAN-EG-77-D-03-1487 for "Engineering and Economic Studies for Nonelectric Applications of Geothermal Energy." Primary interest under this PRDA was for site specific studies dealing with industrial processing, agribusiness (agricultural and aquatic uses), and space/water heating and cooling for commercial and residential buildings. In the third quarter of 1977, the DOE/SAN office issued a Program Opportunity Notice (PON) EG-77-N-03-1553, "Direct Utilization of Geothermal Energy Resources - Field Experiments." The primary interest under this PON was for field experiments in space/water heating and cooling for residential and commercial buildings, agriculture and aquacultural uses, and industrial processing applications. The LBL involvement in the PRDA and PON included technical review and evaluation, and written comments submitted on monthly, quarterly, mid-term, and final study reports. Site meetings were attended when necessary.

In April-May 1977, the California Energy Resources Conservation and Development Commission (Sacramento) issued RFP 500-038, "Direct Heat Utilization of Geothermal Energy Demonstration Project." LBL was asked to participate as a member of the Technical Advisory Committee to evaluate responses to the RFP. The resulting contract award is for the "first" public-funded Direct Heat Geothermal Demonstration Project in California. A space heating project in Mammoth Lakes Village is to be operational early in 1978.

PLANNED ACTIVITIES 1978

The DOE PRDA-DGE/SAN EG-77-D-03-1487 and PON-EG-77-N-03-1553 resulted in four contracts awarded and five to ten contracts under negotiation, respectively. LBL will continue technical assistance in monitoring and reporting on these contracts.

GEOTHERMAL EXPLORATION TECHNOLOGY

The geothermal exploration technology program at LBL began in 1973 in response to an AEC desire for a small geothermal demonstration plant in northern Nevada, where numerous hot springs exist. Scientists at LBL and the University of California were requested to assist with site selection by performing geological, geochemical and geophysical investigations in selected promising areas. Although the goal for a demonstration plant was later dropped by ERDA, LBL was requested to continue with the research, changing the emphasis from site selection to exploration technique development and demonstration. As a result, conventional as well as less standard exploration techniques were tested. Available state-of-the-art equipment and techniques were used, but where these were either unavailable or inadequate for the task, new hardware and computer methods were developed by LBL. Among these were instruments and techniques for sampling and analyzing spring waters, up-down counters (signal averagers) and synchronous detectors for use in electrical-electromagnetic surveys, a modern seismic system, and various new computer techniques for data processing and interpretation. Although the northern Nevada work has been concluded and numerous topical and site-specific reports have been issued on the work accomplished, the geothermal exploration technology program continues with two objectives:

1. to apply and transfer new technology by means of field surveys at geothermal areas, and

2. to extend the state-of-the-art by developing new and improved exploration instruments and data processing/interpretation techniques.

SEISMOLOGICAL INVESTIGATIONS

T. V. McEvilly, E. Majer, A. Liaw, and B. Schechter

INTRODUCTION

At the project beginning in 1973, the usefulness of seismological techniques for geothermal exploration was largely unknown. Plans were made to study microearthquake occurrences and the nature of ground noise (microseisms) in several potential geothermal areas in north-central Nevada, to evaluate these passive seismic methods for both reconnaissance and detailed exploration.

To this end, a modern, trailer-mounted, 12-station, radio-telemetered seismic network was fabricated, using commercially available electronics and slow-speed magnetic tape recording. A dynamic range of 40 dB, 0-80 Hz was achieved when equipment was well-maintained.

Extensive data collection was conducted in Nevada, largely in Grass Valley, including an experiment involving the use of active seismic technique for geothermal exploration. Additional studies were conducted at The Geysers geothermal field, California using the basic portable network and a new triggered digital field recorder acquired by the Seismographic Station, U.C. Berkeley, for high-resolution spectral studies.

Cooperative programs of seismological studies, instrumentation and data analysis were begun for both the Raft River, Idaho and East Mesa, California geothermal areas.

The overall goal of the program remains the acquisition of high-quality seismological data from well-planned experiments at differing geothermal environments. Although a great deal has been learned about the acquisition, processing and interpretation of seismological data, crucial questions remain on the utility of seismic methods in reservoir detection and delineation, and on the proper experimental techniques, for both active and passive surveys.

ACCOMPLISHMENTS IN 1977

A major element of the program was completed in 1977 with the conclusion of a study of microseisms (ground noise) in exploration.[1,2] A significant conclusion based on data obtained around Leach Hot Springs, Grass Valley, Nevada is that the ground noise is composed mainly of fundamental mode surface waves and these waves are of limited exploration value. As conventionally studied in terms of their amplitude spectra, these waves offer information on the location of lateral variations in shallow rock properties, for example, changes in the thickness of alluvium, particularly at faults. The waves also give direct evidence for very shallow hydrothermal activity such as boiling springs. However, a frequency-wavenumber analysis of data obtained from carefully designed geophone arrays did not reveal the presence of body wave emissions from a "geothermal reservoir region" at depth below the surface manifestations. Whether certain types of concealed geothermal systems can be detected and recognized from thermally-induced body wave radiation remains an unanswered question. Additional field experimentation is needed at various geothermal systems. The data necessary to answer the question would best be obtained using a large, multi-component acquisition and recording system, such as are currently used by seismic reflection crews.

Other seismological studies in Grass Valley, which include the evaluation of microearthquakes, P-wave delays and seismic reflection-refraction surveys, constitute part of a Ph.D. dissertation to be completed in early 1978.[3] Similar investigations were also conducted at The Geysers[4], permitting comparisons for the two contrasting geothermal systems (one a large, vapor-dominated system, the other a small, cooler, liquid-dominated system). Results indicate that both are characterized by high velocity and low attenuation within the known or suspected reservoir area. Although local earthquake activity was low in Grass Valley and not related to Leach Hot Springs, small earthquakes are numerous at The Geysers and their locations suggest a possible correlation with the boundary of the major steam production zone.

PLANNED ACTIVITIES IN 1978

The successful application of seismological observations to geothermal reservoir detection, delineation and monitoring will require a field system capable of collecting and processing, in the field, data from many channels. To be useful to industry the system must also be cost-effective, that is, have a low operating cost, far less than that of a conventional seismic reflection system. To this end, we have begun design of a special-purpose field system capable of performing on-line many of the necessary analyses which presently can only be done by post-field processing.

Seismological field activities in 1978 will be extended to the Cerro Prieto geothermal field, Baja California, Mexico, under a cooperative international agreement between DOE and the Mexican electric utility, CFE. Data collected at this producing field (75 MW currently with an additional 75 MW planned for 1978) will be analyzed and compared with results from other geothermal areas studied by LBL, which are The Geysers, East Mesa, and Leach Hot Springs.

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EAST MESA SEISMIC STUDY

T. V. McEvilly and B. Schechter

INTRODUCTION

Magnetic tape records of data collected by the U.S. Bureau of Reclamation at their six-station seismic network around the East Mesa geothermal field were analyzed. The purposes of this study are: (1) to obtain further details of the faulting and associated stress fields as defined by local earthquakes; (2) to infer the properties of subsurface rocks from the characteristics of the P- and S-waves generated, including wave velocities, Poisson's ratio, and attenuation; and (3) to provide USBR personnel, and others, a set of procedural guidelines for subsequent analysis of network data.

ACCOMPLISHMENTS IN 1977

The first tapes analyzed were from April 1977, and these served to improve instrumental characteristics and to help correct deficiencies in the network. Subsequent data were searched for reservoir-related earthquakes. To date, none have been detected. In reaching this conclusion, we have systematically identified signals from the bombing range, lightning, drilling activity, and many earthquakes occurring along the Imperial and Brawley fault zones. A distinctive suite of seismic waves, characteristic of the East Mesa area, has been identified. These consist of multiple P- and S-waves, very slow surface waves and air-coupled surface waves. No events have been detected emanating from the reservoir region.

Our findings do not support previous reports of microearthquake activity associated with the East Mesa field. While it is possible that earlier interpretations were correct and seismic activity has decreased, it is also possible that hypocenter locations were incorrectly calculated because secondary P-waves were thought to be S-waves.

Other accomplishments of the study are as follows:[1]

1. An analysis of 10 regional earthquakes shows that the Poisson's ratio is 0.25, a typical value for the crust, and indicating that the S velocity is not anomalous with respect to the P velocity.

2. Two schemes for determining microearthquake magnitude were investigated; one based on coda length, the other on S-wave amplitude.

It was determined that the network sensitivity provides a detection threshold at M = 2.0 for the Brawley area, and probably about M = 1.0 at East Mesa. As there were no clear events from the East Mesa field during several months of record, we can conclude either that activity is swarm-like and we are in a quiescent period, or the seismicity level is lower than thought. In either case, it was recommended to the USBR that the network sensitivity be increased. The simplest approach, which could yield an order of magnitude reduction of the earthquake threshold magnitude, would be to emplace the geophones in shallow holes to avoid near-surface noise. Also, the low-end frequency cut-off should be increased from 1 Hz to 4.5 Hz by use of 4.5-Hz geophones in the holes.

ACTIVITIES PLANNED FOR 1978

Analysis of the tapes from the East Mesa network will continue. Tests of the suggested approach for increasing network sensitivity will be made by installing 4.5-Hz geophones at the surface and in the existing water wells at East Mesa.

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ELECTRICAL AND ELECTROMAGNETIC INVESTIGATIONS

H. F. Morrison, H. F. Beyer, R. Corwin, A. Dey, M. Hoversten, B. Jain, K. H. Lee, E. Mozley, and G. Oppliger

TELLURIC AND DC RESISTIVITY TECHNIQUES APPLIED TO THE GEOPHYSICAL INVESTIGATION OF BASIN AND RANGE GEOTHERMAL SYSTEMS

E-Field Ratio Tellurics

Field instrumentation and data interpretation techniques were developed for the E-field telluric method.[1] The method employs a collinear three-electrode array to measure successive electric field ratios as the array is leap-frogged along a survey line. The 0.05 and 8 Hz responses for numerous simple resistivity structures were calculated by means of numerical modeling. From the model study it was concluded that the method is a rapid electrical reconnaissance technique for deep conductive targets, such as might be associated with hydrothermal systems. It was also shown that the frequencies used for both the model study and the actual fieldwork are appropriate to exploration in Basin and Range valleys, and afford a rudimentary means of depth discrimination.

A Comparison of Dipole-Dipole and Schlumberger DC Resistivity Results

A two-dimensional numerical model study and comparison of the polar dipole-dipole and Schlumberger resistivity arrays was performed.[2] A catalog of dipole-dipole and Schlumberger apparent resistivity pseudo sections was compiled using a computer program developed by Dey[3] and Dey and Morrison.[4] It was demonstrated how interpretational errors arise when Schlumberger data are interpreted by means of one-dimensional inversion and the resistivity structure is not strictly horizontally layered. A disadvantage of the Schlumberger technique is that conductive bodies with a depth burial greater than their width are not resolved. On the other hand, the dipole-dipole array produces complex anomaly patterns unrelated in appearance to the simple causative structures modeled. Hence, familiarity with model results is essential to interpretation of these data.

Interpretation of E-Field Ratio, Bipole-Dipole, and Dipole-Dipole Resistivity Data

A detailed interpretation of E-field ratio telluric, bipole-dipole resistivity mapping, and dipole-dipole resistivity data obtained in the course of geophysical exploration of the Leach Hot Springs area of Grass Valley, Nevada was performed.[5] Several areas were identified as worthy of further investigation on the basis of resistivity anomalies. Comparison of the three electrical exploration techniques indicates that the bipole-dipole resistivity mapping method, a reconnaissance technique, is neither rapid nor capable of providing unambiguous results. Applied correctly, the E-field ratio telluric method can be a useful, low-cost reconnaissance technique for delineating structures and comparing the resistivities of different regions within the survey area.

The dipole-dipole resistivity method is extremely useful, particularly where lateral contrasts occur. However, because of the high operating expenses involved and the difficulty in interpreting results, the method is better used as a detail method unless the interpreter is extremely practiced. As of now there are no automatic two-dimensional inversion schemes for interpreting dipole-dipole data.

SELF-POTENTIAL SURVEYS IN GEOTHERMAL AREAS

Self-potential surveys conducted in a variety of geothermal areas show anomalies ranging from about 50 mV to over 2 V in amplitude, and from about 100 m to over 10 km in width.[6] The polarity of the anomalies may be positive, negative, bipolar, or multipolar, with the steepest gradients often seen over faults which are thought to act as conduits for thermal fluids. In some cases anomalies several kilometers wide correlate with areas of known elevated thermal gradient or heat flow. Laboratory data indicate that thermoelectric or electrokinetic coupling may generate source voltages comparable to observed anomaly amplitudes, but analytical techniques for calculating surface anomalies generated by the subsurface temperature distribution or fluid flow pattern are not yet fully developed. If the electrodes are not watered, and if telluric currents and electrode polarization are monitored, most self-potential readings are reproducible within about ±5 mV. Short wavelength geologic noise of up to about ±10 mV, primarily caused by variation in soil properties, is common in arid areas, with lower values in areas of uniform, moist soil. As self-potential variations may be produced by conductive mineral deposits, stray currents from cultural activity, and changes in geologic or geochemical conditions, self-potential data must be analyzed carefully before a geothermal origin is assigned to observed anomalies.

COMPUTER MODELING TECHNIQUES

Three-Dimensional DC Resistivity

Numerical techniques have been developed to solve the three-dimensional potential distribution about a point source of current located in or on the surface of a half space containing an arbitrary two- or three-dimensional conductivity distribution.[7] Self-adjoint difference equations are obtained for Poisson's equation using finite difference approximations in conjunction with a point as well as area discretization for the two-dimensional case, and an elemental volume discretization for the three-dimensional case. Potential distribution at all points in the set defining the subsurface are simultaneously solved for multiple point sources of current. Accurate and stable solutions are obtained using full, banded Cholesky decomposition of the capacitance matrix as well as the recently developed Incomplete Cholesky-Conjugate Gradient Iterative method. Accurate solutions for models of comparable dimensions are attained with significantly less attendant computational costs than with the relaxation, finite element or network solution techniques.

A comparison of anomalies for the collinear dipole-dipole array over two- or three-dimensional block-shaped models indicates substantially lower anomaly indices for inhomogeneities of finite strike-extent. In general, the strike-extents of inhomogeneities have to be approximately ten times the dipole lengths before the response approaches the two-dimensional value. The saturation effect with increasing conductivity contrasts appears sooner for the three-dimensional conductive inhomogeneities than for corresponding models with infinite strike lengths.

A downhole-to-surface configuration of electrodes produces diagnostic total-field apparent resistivity maps for buried three-dimensional inhomogeneities. Experiments with various lateral and depth locations of the current pole indicate that mise a la masse surveys give the largest anomaly if a current pole is located asymmetrically and preferably near the top surface of the buried conductor.

Computer Model Comparison and Evaluation of Bipole-Dipole and Dipole-Dipole Resistivity Mapping

Bipole-dipole (B-D) resistivity mapping has been widely used as a reconnaissance method in geothermal exploration. In this technique, apparent resistivities are plotted at roving dipole receiver locations and the current source bipole is left fixed. Interpretation to date has been in terms of simple, layered, dike, vertical contact, or sphere models. In the case of more complicated two-dimensional models the interpretation is much more ambiguous and the detection of buried conductors depends very much on the choice of transmitter location. Since B-D apparent resistivities measured on a line collinear with the dipole are roughly equivalent to the apparent resistivities for one sounding in a dipole-dipole (D-D) pseudosection, the two methods have been compared for several two-dimensional models.[8]

A buried quarter-space and a buried horizontal cylinder with rectangular cross section, with or without an overburden layer, have been used in the comparison. Unless the target is very shallow or close to the bipole or dipole, the resolution of the horizontal position or depth extent for the B-D method is very poor. Conductive overburden worsens the situation for both methods but the effect is more drastic for the B-D method. The spatial patterns for these models are complex for the B-D method and in fact for certain transmitter positions only subtle differences exist for the buried cylinder and buried quarter-space models. Multiple sources improve the resolution of the B-D method, but many sources coupled with the high sampling density of receivers required to define the spatial patterns would greatly reduce the cost-effectiveness claimed for this method. Changing the bipole orientation with respect to the strike of the models contributes little if anything to the resolution of the models. A further experiment of calculating a residual map by subtracting the half-space or layered half-space response from the response of the buried models was also unsuccessful in improving the interpretability of the B-D method. Finally, a model representative of a typical Basin and Range valley with or without a hypothesized geothermal reservoir shows that in more complex models the B-D map would not, in a practical survey, reveal the reservoir.

From these model studies, it is clear that except for some simple geologic situations, the B-D method is not effective for subsurface mapping. Selected D-D lines would be far more useful and more cost-effective.

Comparison and Analysis of Least-Squares Algorithms Used for DC Resistivity and EM Inversion

The interpretation of DC resistivity and EM soundings has been a topic of research since the early 1930's. In recent years many least-squares minimization algorithms have been developed, following different approaches, for use in the inversion of sounding data. The efficiency and accuracy of an inversion technique depends both on the mathematical approach used and on the nature of the physical system producing the measured fields. In regard to the latter, the speed and accuracy of a particular algorithm is dependent on 1) the type of model chosen to fit the data, and 2) the initial estimates of model parameters.

In 1977 work began to compare five widely used inversion algorithms, and to examine the statistics of the individual and combined effects of model parameters on the fields.

The comparison of algorithms was made in terms of speed and accuracy in finding a solution to a set of input data generated for a specific model. Two geologically important models were used in this study: a thin conductive layer in a resistive host, and a thin resistive layer in a conductive host. The results of the tests and descriptions of the algorithms will soon be published as an LBL report.[9]

The statistical evaluation of model parameters is based on the eigenvector-eigenvalue decomposition of the system matrix, $\tilde{A}$, where $\tilde{A}$ is composed of the partial derivatives of the measured field data with respect to all model parameters. This type of analysis allows one to evaluate the effects of individual and multiple parameters on the data, and to determine the expected limitation on parameter resolution from a particular data set.

Work in 1978 will include continuation of the statistical study of model parameters and the sensitivity of data to variations in these parameters. As an extension to this work we hope to develop an integrated inversion algorithm for complicated geologic situations. This would be used to develop a field method for combined frequency and geometric sounding to separate the electromagnetic induction effects of a near-surface conductive layer from those of a buried conductor. This is needed because a near-surface conductor will completely mask the effects of a buried conductor if the wrong geometric configuration (that is, source-receiver location) is used in a frequency sounding.

Three-Dimensional Electromagnetic Modeling

In 1977 work began to develop a reliable computer code which will simulate the electromagnetic response of a three-dimensional conductivity distribution. The Integral Green's Function Method, as used previously by Weidelt[10] and Meyer,[11] is being used to solve this EM scattering problem. The applications of this code are many. For example, it would allow quantitative comparisons of natural field and controlled-source electromagnetic methods for realistic geological situations. The code would also permit description of EM field variations in the vicinity of a finite conducting body, and this will aid in the interpretation of EM measurements in a complex geologic region.

Of immediate importance, the code will be an aid in the interpretation of actual EM field results obtained at geothermal resource areas. One such area is Mt. Hood, Oregon, where magnetotelluric and telluric measurements were made in 1977. The region is geologically complex and the subsurface conductivity distributions are expected to be complex also. Three-dimensional model simulations will be required to obtain an accurate interpretation for the conductivity distribution.

During 1977 an existing code was modified, tested, and evaluated. Stability problems were encountered and it was concluded that a new code was required to optimize the calculations. This work was initiated.

Activities planned for 1978 include completion and evaluation of the new Integral Equation code. We also plan to evaluate new numerical techniques that may be more efficient and versatile than the ones in use. Finally, the codes will be used to compare response from various types of EM sources and to compare the responses of three-dimensional structures to controlled-source and natural field excitations.

In particular, work will be continued on the problem of an arbitrarily polarized magnetic-dipole source above a two-dimensional half-space. The theoretical base is the variational principle and the numerical technique used is the finite element method. The region of interest, including the air, is divided into many rectangular elements in which the field behaviors are assumed to be quadratic.

By Fourier transforming out the strike direction, we only have to integrate over the cross-sectional area normal to strike. Although three components of magnetic field remain in transformed space, we will attempt to express one in terms of the other two through the divergence theorem.

The boundary condition will be a mixed one obtained by making use of the intrinsic impedance of the plane wave at the boundary.

Magnetotelluric Modeling

Late in August 1977 a finite-element program was developed for modeling both the TE and TM mode plane wave scattering from an arbitrary two-dimensional structure. With the introduction of a new matrix inversion technique, the program is about five times faster than an older TEM program. The greater computational efficiency has allowed us to do magnetotelluric (MT) modeling that was impractical before, and the MT response for a number of fairly simple two-dimensional models were calculated. Choice of models was determined by our need to interpret MT results from Grass Valley, Nevada, and the models are all related to Basin and Range structures and resistivities.[12]

A catalog of calculated TEM responses was prepared for about 12 models and these curves were compared to the MT results. This has provided a great insight into how parameter variations for two-dimensional structures affect MT results and how errors occur when one-dimensional inversions are used to interpret "two-dimensional" data, particularly the data from stations close to the edge of a valley.

A study was also begun on the possible use of the magnetotelluric "tipper" for MT reconnaissance, the tipper being defined as the ratio of the vertical magnetic and horizontal magnetic field perpendicular to geologic strike. Based on the two-dimensional model studies it was found that tipper amplitude is a maximum near a vertical contact and tipper direction is always toward the more resistive side of the contact. While the basic tipper parameters (strike direction, amplitude, and dip direction) do not provide enough information for a detailed interpretation, these parameters help to delineate two-dimensional structures and identify three-dimensional structures. Therefore, in geologically complex areas a conventional MT survey might be preceded by a reconnaissance tipper survey to assist MT survey planning.

Activities in 1978 will include the following:

- The basic MT data processing computer program MAGTEL will be completely rewritten to accommodate multiple channels of input data as obtained in remote telluric-magnetotelluric surveys.
- A program to calculate the statistical errors in reference magnetometer-magnetotelluric data processing will be completed.
- Additional two-dimensional models will be added to the catalog of TE-mode and TM-mode model calculations, and a computer program will be completed to present these results in concise pseudo-section form.
- A new modeling technique for TM-mode, plane-wave scattering will be investigated. This technique, based on the integral equation approach, provides a rapid way of calculating the response from small, two-dimensional bodies with simple shapes.

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STATE-OF-THE-ART ASSESSMENT OF SURFACE GEOPHYSICAL TECHNIQUES

N. E. Goldstein, M. Wilt, and R. Norris

A state-of-the-art assessment of surface geophysical techniques was made to identify gaps or weaknesses in the technology, as applied to geothermal exploration, and to suggest solutions. Four general classes of methods were considered: passive seismic, active seismic, natural field electrical and electromagnetic, and controlled-source electrical and electromagnetic.

For each method class, the specific techniques reviewed are listed in Table 1. The approach followed, broken down by method class or specific technique, was to:

1. Perform a state-of-the-art assessment using (a) the expertise of geophysicists at LBL and the University of California who have been involved in the Geothermal Exploration Technology Project, (b) the current literature, and (c) the expertise of geophysicists in industry and other academic/laboratory circles.

2. Identify areas where additional research is needed to improve the geophysics and also make it more cost-effective.

Table 1. Geophysical methods considered in research planning.

Passive seismic	Active seismic	Natural field electrical and electromagnetic	Controlled-source electrical and electromagnetic
1. Background microseisms (ground noise)	1. Refraction	1. Self-potential	1. Galvanic electrical resistivity
2. Micro-earthquakes	2. Reflection	2. Tellurics	2. Induced polarization
3. Teleseismic earthquakes (delay and attenuation)		3. Magnetotellurics (MT)	3. Controlled-source electromagnetics
		4. Audio-magnetotellurics (AMT)	
		5. Audio-frequency magnetics (AFMAG)	

3. Provide a problem statement and a suggested solution for each research area, from which a preliminary work statement and research plan could be written.

Although not yet undertaken, there is a plan to select an external review committee composed of geophysicists from industry, government and academia who would be responsible for reviewing the plan, suggesting priorities, preparing preliminary schedules and level-of-effort estimates, and submitting their comments and recommendations in writing to the Program Manager, Division of Geothermal Energy (DGE), Department of Energy (DOE).

ACCOMPLISHMENTS IN 1977

The state-of-the-art assessment was completed (Goldstein, Wilt and Norris, 1978) and although the final report has not been issued, a draft report has been submitted to the DOE/DGE Program Manager. The major conclusions are summarized here. Figure 1 is an example of the research matrices that were used in the report to graphically illustrate the workings of each research project and how the project's components interrelated. The components are categorized as: fundamental studies, instrument development, data processing, data interpretation, and verification studies (proof-of-concept or proof-of-design investigations).

SUMMARY OF FINDINGS: PASSIVE SEISMICS

Seismic Data Acquisition and Processing

Passive seismic exploration would be more effective if industry had a system with large data-gathering capacity but low operating cost. The ideal system would sample an entire prospect area (10 x 10 km) in one set-up with many geophones and have the capability for some automatic in-field data processing, tape recording and information storage for post-field processing. It would have provision for microearthquake detection and location, and ground noise mapping (both amplitude spectra and array processing). Selected information from teleseismic or regional earthquakes signals might be stored for post-field processing for P-wave delay mapping, and attenuation (Q) mapping.

Ground Noise Studies

An effort should be made to determine whether ground noise studies have a direct application in geothermal exploration, that is, to determine

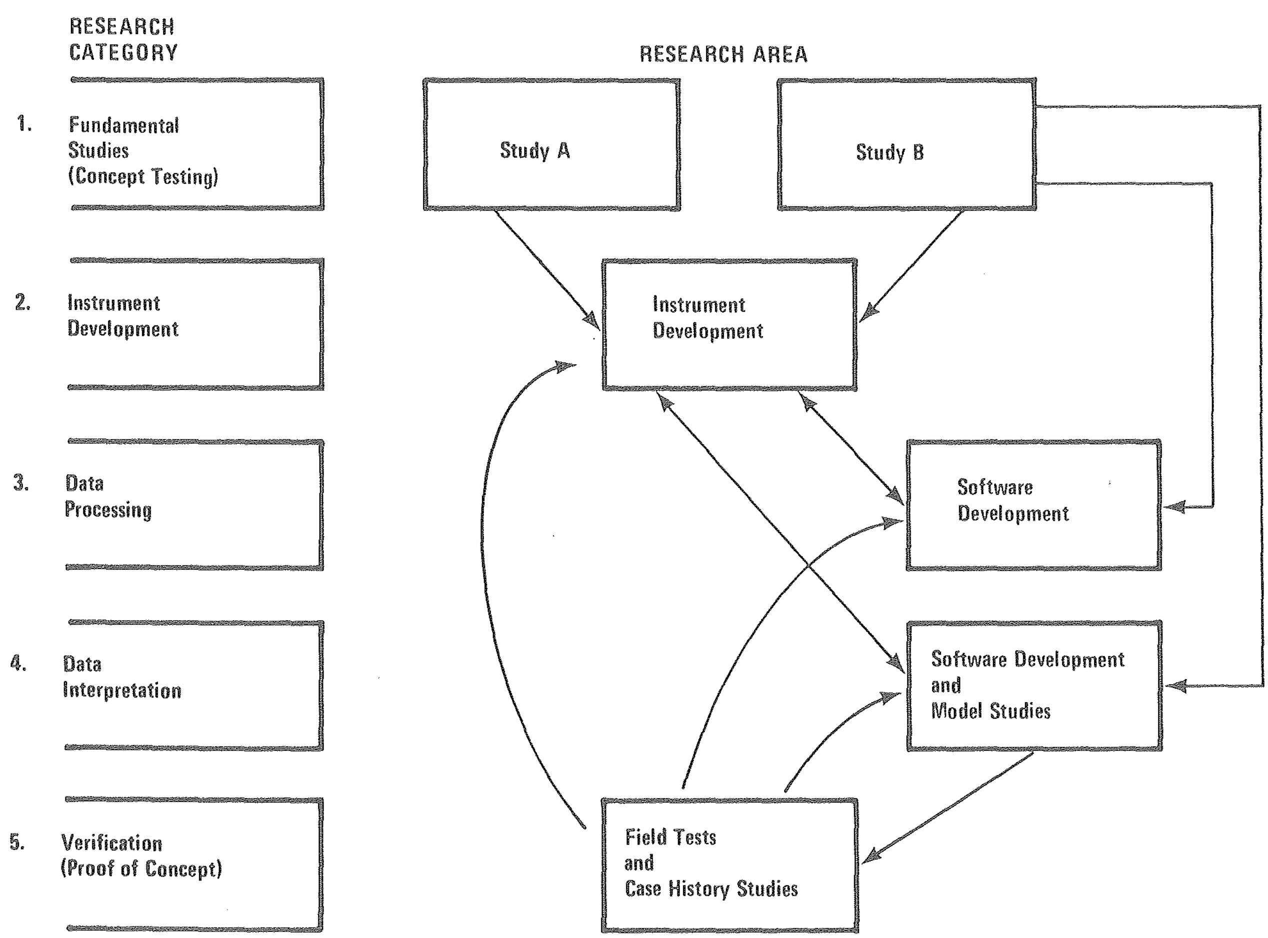

Figure 1. Example research matrix for surface geophysical method.

whether certain types of near-surface geothermal regimes radiate body wave energy, and if so, to define the source mechanism. This information could be used to improve data acquisition and processing procedures. This research might be conducted over a number of reservoir areas using commercial seismic reflection equipment, minus the source, to record noise from a two-dimensional spread.

Magma Chamber Mapping

A careful study of teleseismic P- and S-wave arrival times and attenuations and a study of Rayleigh-wave phase velocity can help determine the presence of molten or partially molten rocks underlying certain geothermal areas.

Microearthquakes and Fault Mapping

Whether thermal conditions (for example, hydrothermal convection) cause "geothermal earthquakes" with identifiable characteristics has not been adequately determined. This would require careful microearthquake studies within and outside known geothermal areas. Systematic differences in source characteristics would be sought.

SUMMARY OF FINDINGS: ACTIVE SEISMICS

Far more active seismic exploration work may be done than is commonly known and reported in the published literature. For this reason, segments of the geothermal industry, particularly smaller companies with little background in seismology, may have scant appreciation for active seismic applications to their exploration problems. A one- or two-day symposium on this subject is recommended, with the success of it being largely dependent on the participation of oil companies experienced in this area.

Seismic Refraction Studies

The usefulness of P-wave delay and P- and S-wave attenuation mapping for geothermal exploration should be tested by means of large-scale experiments at several geothermal systems. Both large magnitude, distant earthquakes and explosion sources would be utilized. The objectives would be to determine whether mineralogical/physical property differences of the reservoir regions causes perturbations in seismic wave characteristics and to relate this information to reservoir characteristics.

Fault Mapping

Improved high-resolution seismic reflection data acquisition and processing techniques should be tested at geothermal reservoirs where faults and fault-controlled permeability are important. Tests should be designed to determine procedures for extracting accurate information on fault location and geometry.

V_p/V_s, Poisson's Ratio Sections

Additional work is needed to investigate the usefulness V_p/V_s sections for geothermal exploration and reservoir delineation. Laboratory evidence suggests that small amounts of steam will lower V_p/V_s, but field evidence at The Geysers is conflicting. Additional field work is needed, utilizing large-force shear-wave generators as well as local microearthquakes. Development of an efficient, combined SH- and P-wave energy source is also a worthwhile adjunct to this work.

Deep Crustal Studies

The value of deep crustal (low resolution) reflection soundings for geothermal exploration is largely unknown. Surveys of the type being performed under the present COCORP Project may provide some important information on this subject and may be useful as a guide to future research.

Laboratory Studies

Additional laboratory studies of rocks under simulated geothermal reservoir conditions are needed for an understanding of elastic wave propagation in these environments. These studies must be carefully made, researchers must be mindful of irreversible changes that can take place once the sample is extracted from the earth, and the results must be studied in relation to well logs and surface measurements.

SUMMARY OF FINDINGS: NATURAL FIELD ELECTRICAL AND ELECTROMAGNETIC METHODS

Self-Potential

Self-potential (SP) research areas should include 1) self-potential data base, 2) origin of self-potential anomalies, and 3) electrode studies.

1. Acceptance of SP as an important exploration technique may depend on the acquisition and publication of an adequate laboratory and field data base. A catalog of field results, supported by other surface and subsurface geological and geophysical information, is needed for anomalies of both geothermal and non-geothermal origin.

2. There is insufficient understanding of the causes of natural SP anomalies related to geothermal processes. Process information is needed to determine whether discrimination between geothermal and non-geothermal SP anomalies is possible. Laboratory studies on rocks and cores are needed to obtain magnitude estimates of streaming and thermoelectric potentials under geothermal conditions.

3. Self-potential measurements can be improved by finding ways to avoid the electrochemical effects (noise) which occur between electrode and ground. Proper electrode selection may be helpful because certain type(s) of electrodes may be more stable than others depending on local conditions, for example, soil moisture, saturation, soil chemistry, temperature changes, moisture transpiration rate.

Tellurics

Studies in tellurics should deal with 1) the separation of local from regional effects, 2) updating vector telluric recording systems, and 3) data interpretation.

1. Regional structure may induce nonuniformity to the telluric field, thus obscuring smaller, local effects. There is no way to eliminate this problem, but effects can be studied and compensations estimated by means of calculations for two- and three-dimensional structures.

2. The vector telluric survey system can be improved to varying degrees. Maximum improvement would be achieved if most of the usual post-field data processing were eliminated by means of an in-field data acquisition and processing system designed around a minicomputer. Alternatively, simpler systems based on microprocessors could be used to obtain some of the numerical parameters, which after being recorded, could be more fully processed in the laboratory. Lastly, the option requiring the least development is a system in which total post-field processing could be retained, but made more effective by recording data on digital cassette recorders.

3. Interpretation of vector telluric data in geologically complex areas requires the numerical solution for the electromagnetic response of inhomogeneous half-spaces. Suitable computer programs are developed and used for magnetotelluric interpretation but have not as yet been applied to the telluric cases.

Magnetotellurics

Magnetotelluric (MT) research should cover 1) effects of geologic and man-made noise, 2) data processing and noise reduction, 3) remote telluric-magnetotellurics, 4) modeling and interpretation, and 5) tipper reconnaissance.

1. Data can be influenced by natural and man-made noise which is sometimes difficult to recognize, and leads to improper interpretation of impedance estimates. Among these effects are large-scale field distortion caused by regional geology, non-planar signals caused by local atmospheric and man-made electrical disturbances, and local geologic inhomogeneities whose effects depend on the length of electric dipole used. These problems are serious and difficult to address. Suggestions for additional and/or continued efforts include: (a) analog and mathematical models for representative regional geological structures, (b) collection of regional MT data in areas of geothermal interest, (c) a study and categorization of local man-made noise disturbances, and (d) more detailed studies of electric dipole length on impedance estimates in areas of geothermal interest.

2. Standard processing techniques will give biased and scattered estimates whenever electromagnetic noise is present. Thus, better data acquisition and processing techniques are needed. In addition, an understanding of the nature of electromagnetic noise is important, and may have significance to geothermal exploration as well. Efforts in these areas have begun and should be continued. Among the on-going activities are attempts to develop impedance calculation approaches that are less sensitive to noise or that can be used on short data segments, and to develop new data acquisition techniques that allow one to recognize and compensate for certain types of noise.

3. The remote telluric-magnetotelluric (T-MT) method offers one means for improving the speed and cost-effectiveness of MT surveys. Whether this approach is only effective in areas of homogeneous, layered structures or may be applied to more complex areas is a subject that needs to be studied and evaluated. Also, because many simultaneous channels of data are collected in the T-MT technique, an on-site data processing system is desirable.

4. The magnetotelluric method is severely handicapped by the user's inability to interpret results in geologically complex areas, where the one-dimensional model does not yield meaningful results. Accurate and efficient two- and three-dimensional computer programs are slowly being developed, but more effort is needed in this direction as many existing computer codes are expensive and difficult to use, requiring machines with large memories. MT interpretations can also be improved by means of joint inversion techniques involving complementary geophysical data sets. The question of whether the MT method is actually capable of detecting a zone of partial melt within the crust needs further study and clarification based on a combination of rock property studies and computer modeling.

5. Planning an MT survey in a geologically complex area might be made easier if the work were preceded by a rapid reconnaissance, using only the magnetic field components to obtain tipper information. Theoretical calculations indicate that one can use tipper amplitude and direction to locate two-dimensional vertical discontinuities and determine whether three-dimensional structures are present.

Audio-Frequency Magnetotellurics

The AMT method is basically a higher frequency version of magnetotellurics. Therefore, AMT is more suitable for rapid reconnaissance, but its depth information is more limited. The problems of AMT are not much different from the problems encountered for MT, given above. AMT studies should deal with 1) elimination of bias and scatter, 2) improvement of field systems, and 3) frequency dependent resistivity effects.

1. AMT results are often degraded by bias and scatter, and present data acquisition systems are unable to detect or eliminate causative noise. These problems may be more severe in AMT than MT, because surface inhomogeneities, source direction, and man-made noise are more prevalent or have a greater influence on results. These problems need to be isolated and studied individually and systematically.

2. Present field systems have limited capabilities and should be improved. In particular, AMT data acquisition and processing systems are needed which can evaluate data quality, calculate impedance phases, and obtain apparent resistivities down to frequencies approaching 1 Hz. For these capabilities the system requires microprocessor technology for on-site data processing and interpretation, digital recording on magnetic cassettes

for post-field processing (optional), and high-sensitivity, portable magnetometers with a wider frequency range than currently available.

3. Rock resistivities vary, tending to decrease with increasing frequency over the AMT range. While this effect may not often be large enough to cause erroneous and misleading AMT interpretations, the effect may be large in certain geothermal environments. A laboratory study of the frequency-dependent resistivity of rocks in geothermal regimes should be undertaken to better evaluate the application of AMT and IP methods.

Controlled-Source Electrical and Electromagnetic Methods

Under this class of methods we consider galvanic electrical resistivity, induced polarization and electromagnetic induction. The research areas identified are as follows: 1) two-dimensional interpretation of resistivity data, 2) magnetometric resistivity, 3) inductive coupling effects in induced polarization, and 4) controlled-source electromagnetic surveying.

1. Most apparent resistivity data, whether from galvanic or inductive methods, must be interpreted in terms of two- or even three-dimensional models; the easy-to-use one-dimensional interpretations are usually inadequate. Despite many recent advances in computer programming, interpretation based on two-dimensional models is slow and arduous, requiring many trial-and-error forward calculations. Interpretations for three-dimensional models are in their infancy, limited to simple structures. For these reasons we suspect that much of the resistivity data collected by industry has not been properly interpreted. The waning interest in resistivity methods may be due in part to industry's inability to allocate the proper amount of effort to interpretation. Faster, more automatic two-dimensional methods must be developed, and work must continue to optimize three-dimensional model algorithms.

2. The magnetometric resistivity method (MMR) is not known to have been applied to geothermal exploration. Compared to galvanic resistivity, MMR has certain advantages in terms of speed, less sensitivity to surface inhomogeneities, and greater sensitivity to bedrock conductors beneath overburden. MMR should be evaluated by means of field tests at several geothermal areas where supporting information exists. At the same time it is worthwhile to study the magnetic induced polarization (MIP) effect, for this approach may be less sensitive to inductive coupling effects than conventional IP (see below).

3. Despite geological arguments for the applicability of induced polarization (IP) in certain geothermal regimes, the technique is not being used. Of the several possible reasons, one of the likelier is that inductive coupling errors, which have the appearance of true IP anomalies, are large in conductive areas and can be neither avoided by proper field procedures nor easily and accurately corrected for by post-field processing. Research is needed to find a procedure whereby the inductive coupling effect can be determined directly and specifically for each group of implanted electrodes.

4. Controlled-source electromagnetic techniques have advantages over both dc resistivity and natural field resistivity techniques. The development and demonstration of controlled source methods for exploration at depths of several kilometers has been impeded for several reasons. Among these are instrumental and procedural difficulties in generating and measuring the low-frequency fields, and the difficulty of interpreting the results when the earth cannot be approximated by a simple model. Advances in technology now make it possible to build a practical large-moment system covering the 10^{-3} to 10^{3} Hz range and to interpret results from more complex areas. One problem is the source; ideally it should have a large moment, be easy to deploy, retrieve and move in the field, and be oriented for optimum signal-to-noise. Although the most practical transmitter at this time is a relatively small-diameter, multi-turn horizontal loop, this transmitter is not ideal. A rotating dc magnet would be better but to achieve the large moment needed, a lossless dc superconducting magnet would have to be designed for this application.

CONTROLLED-SOURCE ELECTROMAGNETIC SYSTEM

H. F. Morrison, G. Oppliger,
C. Riveros, B. Jain, and N. E. Goldstein

INTRODUCTION

As part of the geothermal exploration investigations in Northern Nevada, field tests were made in 1976 of a pre-prototype EM System pieced together from components on hand. Despite the primitive nature of the equipment, interpretable data were obtained, yielding EM sounding results that compared favorably with the results from other electrical techniques.[1,2] Because of these encouraging results and because such a system would fill a technological gap in geothermal exploration, an engineering study to design a proper system was begun. The system, designated EM-60, would consist of two sections: (a) a transmitter section consisting of the power source, switching electronics, control units and transmitter, and (b) a receiver section consisting of a multichannel synchronous detector, telemetry and phase referencing circuits and a three-component, high sensitivity magnetometer. Design goals included, among other details discussed below, a system that would be inexpensive to build and operate and that would provide useable information over a wide frequency range (10^{-3} to 10^{3} Hz), thus permitting EM soundings to depths of several kilometers. As the system was conceived it would have several advantages over conventional (galvanic) dc resistivity surveys: it would have no long wires to lay out, retrieve and move; there would be no need to make direct electrical contact with the ground; it would be less affected by local surface inhomogeneities; and it would make possible faster surveys using a combination of geometric surveying (changing source and receiver locations) and parametric surveying (changing frequency), that is, a number of depth soundings from one transmitter location.

In addition, the system would have some advantage over natural field magnetotelluric surveying because information would not be missed due to low natural field strength in certain frequency bands.

The transmitter section was to be designed and assembled by engineers at LBL, where the motor generator and other components were already available. The synchronous detector for the receiver section was to be designed and assembled by engineers in the Department of Materials Sciences and Mineral Engineering, Engineering Geosciences, University of California, Berkeley, where expertise was available on microprocessor-controlled synchronous detectors. An existing three-component SQUID magnetometer was to be used initially as the sensor, but because of the magnetometer bandwidth limitations it was recognized that an improved sensor would ultimately be needed. For this reason, consideration was also directed toward designing a SQUID magnetometer with a higher upper frequency than currently existing.

ACTIVITIES IN 1977

Transmitter Section

One of the major design considerations for the transmitter section was to obtain a large dipole moment, $M > 10^{6}$ mks, by means of a relatively small-diameter, horizontal coil. This type of transmitter coil was selected for ease of operation. Inductance has to be kept low to maximize the effective frequency range. Loop diameter has to be relatively large to maximize moment and reduce inductance, but the loop diameter must also be kept small enough to facilitate field operations. Based on previous experiences, field crews found the size 4/0 welding cable to be easily handled, and a 30-meter-diameter, multi-turn coil of this wire was selected.

To drive the coil an available 60-kW truck-mounted motor generator set was refurbished. The necessary switching system was designed, fabricated and tested. Because of the inductive load and large current, neither SCR's nor mechanical switches were feasible. A switching array consisting of transistors (International Pacific, Model IR 5066, 900 volt) mounted in modular, parallel arrays was designed to handle the source which alternates between +150 V and −150 V, up to 400 A. The actual current in the load is compared to a selected value and the symmetry of the waveform is changed to provide the correct current. This is done automatically by means of a feedback system without the need for special tuning capacitors. The design includes generous use of fuses, protection diodes, shutdown logic and varistors.

The EM-60 transmitter is operated from a remote panel that can be placed away from the noise of the motor generator. The panel allows adjustment of the fundamental frequency to three significant figures over six decades. Current amplitude in the loop is adjustable and can be read to three significant figures. The control unit also contains indicator lamps that monitor operations and control buttons to activate and shut down the system. In addition, a voice intercom is built into the unit, with provision for a hardwire link to the receiver unit.

The electronic, electrical and mechanical designs were completed and the motor generator set and truck was refurbished. By November assembly of all major units was finished. Final debugging and system checkouts were delayed because of relocations involving manpower diversions to other projects with critical timing problems.

Receiver Section

The goal of the work was to design, build and test a lightweight, battery-operated, six-channel digital synchronous detector. The instrument must be capable of accurately measuring the phase and amplitude of local magnetic and electric field signals referenced to a distant transmitter current. Critical specifications for the receiver are an obtainable phase accuracy of 1 mr and a detection frequency range of 0.001 to 1000 Hz.

The work planned for 1977 consisted of:
1) evaluation of system design approaches,
2) system hardware design and development, and
3) development of microprocessor system software.
The Motorola M6800 microprocessor was chosen because of our previous work with it.

As work proceeded, it proved practical to add a full harmonic analysis capability to the receiver. This significantly enhanced the instrument's performance by allowing the detection of the harmonics contained in the squarewave signal produced by the transmitter.

The design approach has produced a flexible, self-contained instrument that will meet the requirements of the controlled-source EM receiver. A specification sheet is shown in Table 1. The receiver is also likely to have direct applications in other active and passive geophysical exploration systems.

PLANNED ACTIVITIES FOR 1978

Dynamic tests of the transmitter section will be conducted first without the receiver and later with the receiver and the telemetry link. System programming and laboratory testing of the synchronous dector will be finished early in 1978.

Table 1. M6800 microcomputer signal processor programmed as a six channel synchronous detector/spectrum analyzer.

Frequency range	1.01×10^{-3} to 1.0 kHz (990 sec to 1.0 msec)
Phase resolution	Better than 0.05 degrees
Number of cycles averaged	Up to 2^{16} cycles
Number of points sampled per cycle per channel	1.0 kHz to 70 Hz: 4 pts/cycle 6.9 to 180Hz: 16 pts/cycle 17 Hz to 0.00101 Hz: 64 pts/cycle
Number of harmonics analyzed	Up to 32, 8, or 2 harmonics for 64, 16, or 4 pts/cycle respectively.
Analog inputs configurations	Six single-ended or differential channels
Input voltage	±5 V signal voltage
Analog to digital conversion resolution	12 bits binary
Synchronization signal	7.68 MHz, TTL internal or external, switch selectable.
Phase reference	Any signal applied to channel 1 acts as phase reference for channels 2 through 6.
Detection algorithm	4 pts/cycle (8-bit data resolution) i. Acquire 16 cycles of data. ii. Stack data, repeat i. iii. Sine and cosine transform of stacked data. 16 and 64 pts/cycle (12-bit data resolution) i. Acquire and stack data continuously. ii. Sine and cosine transform of stacked data.
Quantities output	Amplitudes, phases, number of cycles averaged, harmonic number, period of fundamental, station and run number.
Data output form	5-digit LCD and 6-column thermal printer.
Power consumption	10-15 W
Internal battery life	8-10 hrs continuous
Size and weight	9 x 16 x 16 in., 35 lbs.

The detector design will be expanded to include "time-domain" analysis.

Following local field tests to familiarize a crew with systems operation, the EM-60 will be field tested at one or more geothermal reservoirs, and the data obtained will be compared to results from previous electrical studies. Several possible sites for this work have been suggested: Roosevelt in Utah, Grass Valley in Nevada, and Mt. Hood in Oregon, among others.

Documentation of all essential design features, already begun, will be extended and revised for completeness and accuracy. The final results will be compiled and made available to industry.

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DOWNHOLE FORMATION FLUID SAMPLER

J. A. Apps

The primary goal of this project is to investigate the feasibility of developing a downhole formation fluid sampler which is capable of operating in geothermal wells at temperatures to 275°C (527°F) at well depths to 10,000 ft.

The ability to sample geothermal formation fluids directly, in order to measure their physicl and chemical properties, is currently very difficult or impossible. Most samples collected are either mixtures from several producing formations, or contaminated with water from other sources. This seriously hinders our ability to interpret the reservoir potential of geothermal fields.

The Geothermal and Geoscience Group in the Energy and Environment Divison of Lawrence Berkeley Laboratory is currently involved in over 25 projects funded by DOE. Several of these projects (for example, in East Mesa, Raft River, and Cerro Prieto) would benefit directly from data obtained with an improved downhole formation fluid sampler.

The American Oil Company (AMOCO) has cooperated in formulating this project, and has already invested $150,000 in development of a proof-of-concept tool. AMOCO staff will continue to provide technical assistance to LBL at no charge during the development of an improved sampler. AMOCO staff and field personnel have offered to test the sampler in their wells, which vary in depth from 6,000 - 12,000 ft and have temperatures reaching 120°C (248°F). Several operators of geothermal wells at various sites in the United States have expressed interest in testing the sampler in their own wells.

In order to develop an effective downhole sampler for use in the geothermal industry, a number of features of the existing design need to be modified. These include:

1. Ability to operate at temperatures over 275°C (527°F), which involves problems relating to cable degassing, electrical insulation, lubrication, and explosive charge stability.
2. Abiity to operate at depths greater than 10,000 to 12,000 ft.
3. Reduction in the number of O-rings.
4. Reduction of the redressing time to 4 hr.
5. Replacement of the mechanical cable actuation of the pump with a down well motor. This can be an electric motor, or an internal combustion motor.
6. Ability to take multiple samples at several depths without redressing.
7. Increase in the reliability of the electrical switching.
8. Ability to record at ground level, while the sampler is measuring in the well, the following parameters in addition to pressure and resistivity: temperature, pH, Eh, and flow rate of formation fluid and hence permeabiity of the formation and recovery time of the well.

During fiscal year 1977, a preliminary evaluation of the sampler and the feasibility of making improvements to the design was started. It is expected that this work will be completed in fiscal year 1978.

MOUNT HOOD GEOTHERMAL RESOURCE ASSESSMENT

H. A. Wollenberg, H. Bowman, S. Flexser,
N. E. Goldstein, H. F. Morrison, and E. Mozley

INTRODUCTION

Mt. Hood is a young but dormant volcano situated approximately 80 km east of Portland, Oregon (Fig. 1). In 1977, under the auspices of DOE, with coordination by the State of Oregon's Department of Geology and Mineral Industries, and support by the U.S. Geological Survey, the U.S. Forest Service and various research groups, a project was begun to evaluate the geothermal potential of the volcano. This volcano was selected from several others in the High Cascade Range because of its proximity to a major city, the abundance of federally controlled land on which to work, evidence for high-temperature rocks near the surface, and a growing interest in the region by private industry. Besides the geothermal potential evaluation, a secondary objective of the study was to test and evaluate the site-specific usefulness of various exploration techniques. LBL has the responsibilities for coordinating the geochemical and electrical geophysical aspects of the project.

GEOCHEMICAL STUDIES

The geochemical sector of the project encompasses sampling and analyses of warm and cold spring waters, country rocks, and fumarolic gases, to discern the temperatures at depth in circulating hydrothermal systems, and the pathways the waters may take from their sites of origin into and through hot zones within the mountain.

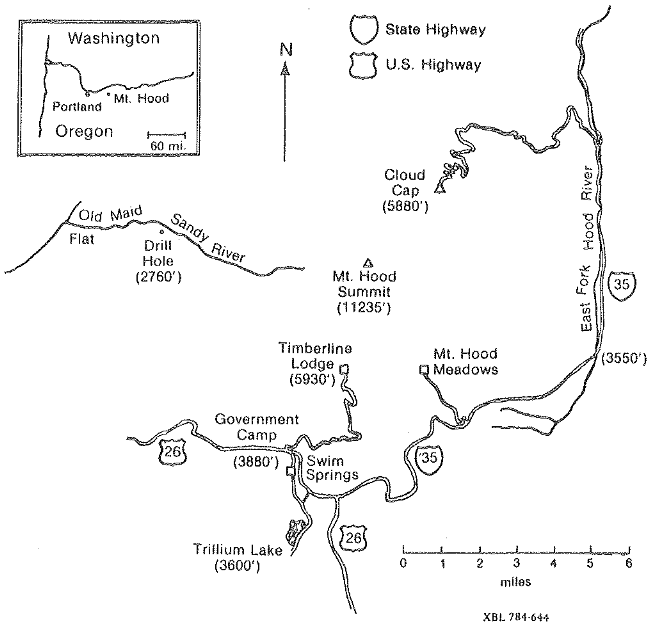

Figure 1. Simplified location map of Mt. Hood area.

Initial sampling of cold and warm spring sources, in conjunction with USGS and State of Oregon personnel, was accomplished in the summer of 1977. Waters were analyzed for trace and major elements by gamma-ray spectrometric, neutron activation and X-ray fluorescence techniques at LBL, and for oxygen and hydrogen isotope ratios by mass spectrometric methods at Saclay, France. In addition, samples of fumarolic vapors from the summit crater area of Mt. Hood were collected in July 1977, and their gas contents analyzed by the USGS geochemical group under the direction of A.H. Truesdell.

Chemical geothermometry and mixing model calculations yielded preliminary estimates of temperatures at depth of hot and unmixed hot waters in the Swim Warm Springs system, on the south flank of Mt. Hood (Table 1).

Table 1. Summary of estimated subsurface temperature at Swim Springs.

Geothermometers	
SiO_2	100–125°C
Na-K-Ca (β=1/3)	214°C[a]
$\delta^{18}O - SO_4$	108–110°C[1]
Silica Mixing Model[2]	
Temperature of unmixed hot water	237°C[a]
Fraction of cold water	0.92

[a] Questionable, because it is a low-flowing system.

A plot of isotope ratios of hydrogen and oxygen for cold and warm spring waters is shown in Figure 2. The points for warm and cold springs fall close to the line for meteoric waters, indicating that the warm waters, strongly diluted by near surface runoff, had little if any interaction with rocks at depth; the warm water points would be substantially shifted to the right of the meteoric water line if there had been appreciable interaction. However, the grouping of the warm water points at the more negative values indicates that the source of the warm spring water is generally higher on the mountain than the sources of most of the cold springs sampled. Exceptions are a spring at Mt. Hood Meadows and a spring in a quarry cut by felsic dikes, well east of Mt. Hood. The grouping of the points indicates that the cold waters have shorter pathways between their sources and the springs, while a component of the warm water may circulate deeply enough in the mountain to come in close proximity to a hot central conduit system.[3]

Future geochemical work on Mt. Hood will include periodic sampling of the several orifices in the Swim Springs area and the spring at Mt. Hood Meadows, to discern the seasonal effects of surface runoff dilution of the warm springs. The fumaroles in the summit crater area will be resampled to obtain abundant condensed vapor, permitting determination of isotope ratios for comparison with ratios of waters from lower parts of the mountain.

Results of major- and trace-elements analyses as well as isotope ratio determinations will be compared with those by White (U. of Oregon)[4] of trace and major elements in Quaternary and Recent

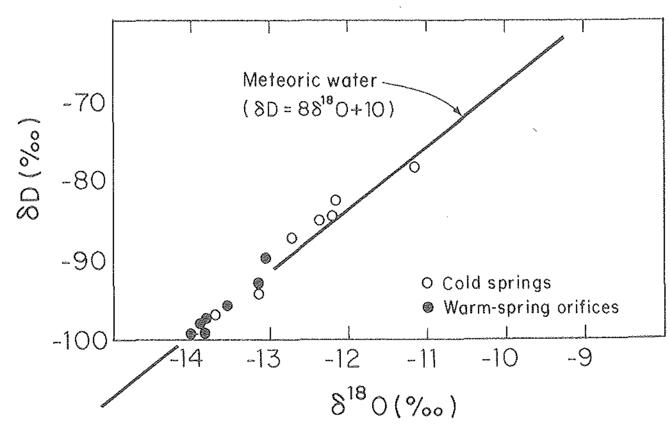

Figure 2. Delta values for oxygen and hydrogen isotopes in Mt. Hood waters. The delta value, given in mils (°/oo), is defined as

$$\delta \text{ in } {}^{o}/oo = \frac{R_{(sample)} - R_{(standard)}}{R_{(standard)}} \times 1000 ,$$

where R represents the isotope ratios of deuterium to hydrogen and $^{18}O/^{16}O$. In this case the standard is "standard mean ocean water."

Mt. Hood eruptives, and strontium isotope ratios determined by Dasch (Oregon State University)[5] on some of the Mt. Hood rocks and waters.

GEOPHYSICAL STUDIES

Accomplishments in 1977

A planning committee composed of experts in electrical methods was convened to discuss and plan experiments on Mt. Hood. The committee decided that the magnetotelluric method (MT), which relies on natural low-frequency electromagnetic energy, would be the initial technique. MT provides deep exploration without the need for long wires and heavy generating equipment, an important consideration on Mt. Hood's rugged terrain. A research plan was formulated which combined an electrical survey with various tests of MT data acquisition and processing. The Mt. Hood work included tests of (a) the telluric-magnetotelluric (T-MT) method, (b) the remote magnetometer (RM) technique, and (c) variable electric dipole length.

(a) Telluric-Magnetotelluric Method

This method, which can reduce the cost of MT surveys, uses one conventional (five-component) tensor MT station (the base station) and any number of remote telluric stations. On the assumption of magnetic field unformity over the area encompassing all stations, magnetic field data recorded at the base station are analyzed with telluric data at base and remote stations to obtain electrical depth soundings for all stations. Because magnetic field uniformity cannot be assumed in areas of complex geology, the validity of the T-MT method was checked by a leap-frog approach, that is, by setting tensor MT stations over previous remote telluric stations.

(b) Remote Magnetometer Technique

Previous MT investigations showed that calculated impedances were biased, particularly in frequency bands where natural electromagnetic field activity was weak. The source of the bias was traced to uncorrelated noise, that is, signal that was not detected uniformly on electric and magnetic channels. Although its origin is conjectural, the noise may be effectively eliminated during impedance calculations if data from a separate reference magnetometer is also used. When the impedances are defined algebraically in cross-spectral terms only, the uncorrelated signals from both sets of data must average to zero.

(c) Variable Electric Dipole Length

Unless a region is free from surface inhomogeneities, the length of the electric dipole and the location of each electrode may bias calculated impedances. In areas of complex geology, compensation is made by using long dipoles to measure the electric field, thus achieving a spatial averaging effect. The trade-offs between suppression of near-surface geological effects and resolution of deeper geologic inhomogeneities by varying dipole length is a subject that has not been adequately studied, either by field measurements or by numerical models. LBL decided to make a start in the direction by conducting tests involving different dipole lengths.

A geophysical contractor, Geonomics, Inc. of Berkeley, California, was selected by LBL to collect the data and to perform the conventional MT analyses. Of several contractors capable of conducting MT surveys, Geonomics was the only one having sufficient instrumental capabilities to perform both the T-MT and RM measurements simultaneously. Eleven channels of information, five from base station detectors and six from remote station detectors telemetered to base, were recorded on a digital magnetic tape. Because of geological unknowns, the MT survey was conducted in two field phases.

Phase I commenced in June and was confined to a relatively small area ($\sim$15 square miles) on the south side of the mountain, below Timberline Lodge. This area was chosen because the relatively good road access would permit a high enough station density to determine whether the subsurface structures are three-dimensional. The area also included the warm water emanations near the Still Creek campground, the only known thermal manifestations other than fumaroles in the summit region. Twenty-nine stations, of which five were duplicates, and two reference magnetometer stations were occupied. One variable dipole-length test was made, and a second test had to be dropped because of time limitations. Results were not uniformly good. Important data at higher frequencies were not obtained at many stations due to serious man-made noise interference and an instrumental problem, which was later corrected. Plans to locate remote telluric stations on the Palmer glacier were not fulfilled. However, subsequent self-potential and profile telluric measurements on the glacier by members of the U.S. Geological Survey showed that the high contact resistances and very high streaming potential voltages would have made our efforts futile.[6]

Significant findings from Phase I were:

(a) The geology appears strongly two-dimensional, oriented north-south, with the more resistive side to the east and outside the Phase I area.

(b) Impedances at the station near the warm springs were definitely anomalous, showing a much higher conductivity extending from surface to depth.

(c) Limited RM processing gave extremely encouraging results.

Phase II commenced in late September and was completed in early November. It was decided to open the survey aperture, that is, to decrease station density and obtain a broader sampling around as much of the volcano as possible. Five clusters of stations were planned, each cluster consisting of two complete T-MT and RM set-ups. One cluster was on the north side, extending northward from Cloud Cap; two clusters were on the east-southeast and crossing the presumed Hood River fault; another cluster was located on the south in the White River area; and the last was on the west in the Old Maid Flat area. All but the last cluster were completed. Only one set-up in Old Maid Flat was made before weather made further work impossible.

Significant findings in Phase II were:

(a) The simple model developed from Phase I results was not confirmed by Phase II. Structural effects were two-dimensional as before, but directed radially toward the summit.

(b) Two stations nearest Cloud Cap, a site of fairly recently erupted volcanics (~2000 years old), were anomalous, showing a very conductive regime.

(c) Validity of the T-MT method was confirmed for the Cloud Cap area.

<u>Plans for 1978</u>

Plans for 1978 include complete processing and interpretation of the Phase I and II data sets. Our basic MT computer program was rewritten to allow RM processing of data. Another new computer program will provide statistical error estimates for all RM-processed data. Interpretation of results will be undertaken by means of additional two-dimensional MT model studies and continued work to develop and exercise an accurate and efficient three-dimensional MT modeling program.

In addition, more electrical survey work is planned to supplement and complement the MT results. At this time, plans have not been finalized, but our general intentions are to acquire near-surface resistivity data missed in the MT work and to conduct detailed surveys in areas of special interest, for example, Still Creek Campground and Cloud Cap.

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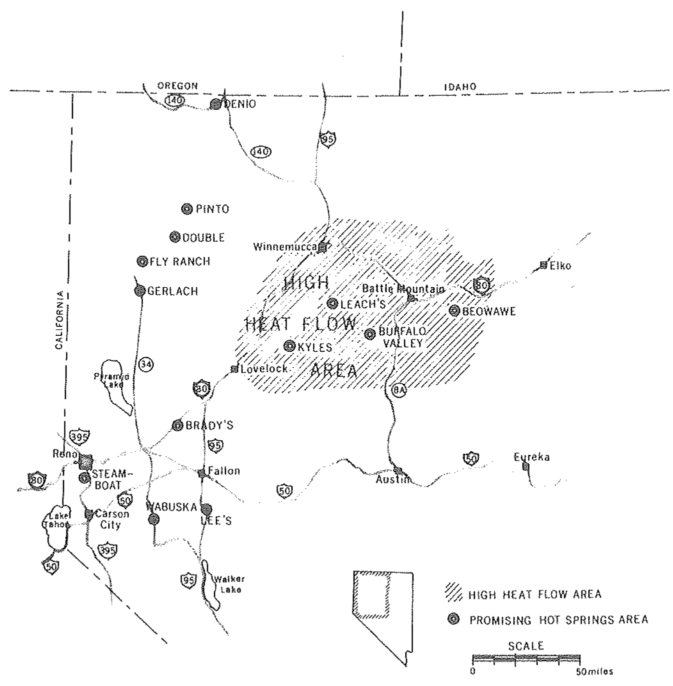
GEOCHEMISTRY OF FOUR NORTHERN NEVADA HOT SPRINGS AREAS

H. A. Wollenberg, H. Bowman, and F. Asaro

As part of the project to evaluate geoscience techniques and to assess the potential of geothermal resource areas in northern Nevada, extensive sampling and analyses of cold and warm water sources were conducted. This geochemical work was done in conjunction with geological and geophysical studies in the same areas.[1-3] The work, begun in 1974, encompassed sampling of waters and rocks in the hydrologic regions surrounding the Beowawe, Buffalo Valley, Leach, and Kyle hot springs areas (a general location map is shown on Figure 1; sampling sites are located on the maps, Figures 2 and 3). Analyses by gamma-radiometric, neutron activation and non-dispersive x-ray fluorescence techniques disclosed the abundances of major-, trace-, and radioelements in country rocks and cold- and hot-spring waters. This permitted application of chemical geothermometers to estimate the temperatures at depth of unmixed hot water in the geothermal systems, and to estimate the influence of country-rock chemistry on the chemistries of the geothermal fluids.



Hot Springs in Northwestern Nevada

XBL 735 676

Figure 1. General location map of Beowawe, Buffalo Valley, Leach, and Kyle hot springs areas.

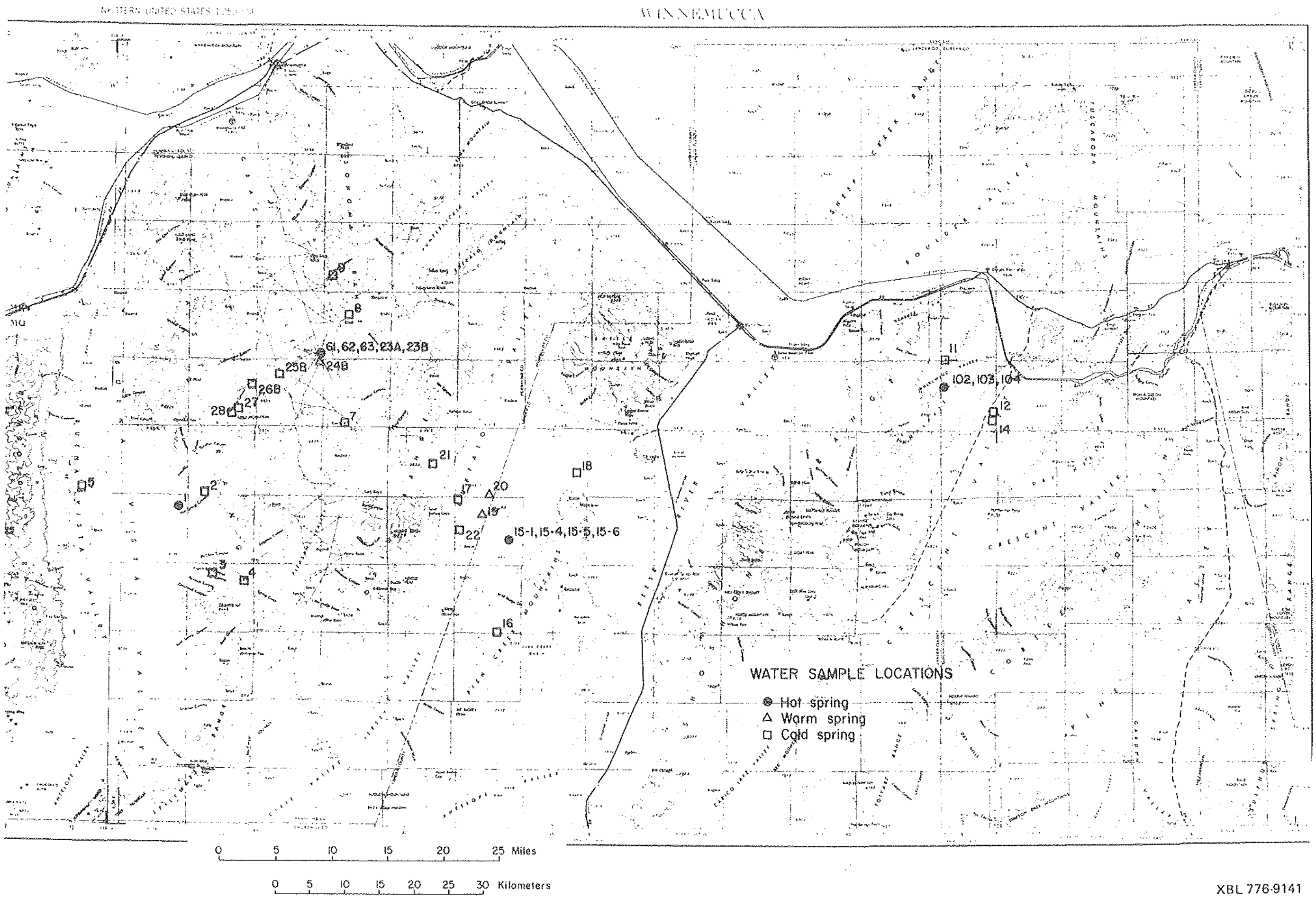


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Figure 2. Water sampling sites for Beowawe, Buffalo Valley, Leach, and Kyle hot springs.

The principal activity in 1977 was to evaluate the analytical data and summarize the results in a report.[4] Conclusions reached in that summary are:

1. Sampling methods, combined with neutron-activation and non-dispersive X-ray fluorescence analyses, give accurate trace- and major-element abundances in rocks and waters.

2. Uranium and molybdenum appear to be concentrated more in cold springs than in hot springs, while other trace elements are generally more abundant in the hot springs. Kyle and Buffalo Valley hot springs which deposit $CaCO_3$, are considerably more radioactive than the silica-dominated springs of Beowawe and Leach. The relatively high concentration of barium in the Beowawe region is reflected in the chemistries of the hot and cold waters of Whirlwind Valley.

3. Mixing model calculations estimated temperatures well in excess of 200°C for unmixed water at Leach and Kyle. These are probably too high, in light of springs water chemistries. The model-calculated temperature, 200°C, of unmixed hot water at Beowawe is close to that determined by alkali-element geothermometry, indicating little near-surface mixing of hot and cold water. The 180°C calculated for unmixed hot water at Buffalo Valley is within the range estimated by alkali-element geothermometers.[5]

4. Contents of tungsten and dissolved H_2S in hot-spring waters may be indicative of subsurface temperature.

5. Uranium is probably concentrating in hot spring systems, on the order of tens of grams per year. If appropriate assumptions are met, a knowledge of uranium parent and daughter isotope abundances may provide sufficient data to estimate the age of the systems.

Information from geophysical surveys was combined with the geochemical data to assess the viability of the hydrothermal systems. For example, Goldstein and Paulsson[6] estimated from gravity data the excess mass of material deposited over the millenia by the geothermal waters at Leach and Kyle hot springs: 2.5×10^8 metric tons at Leach,

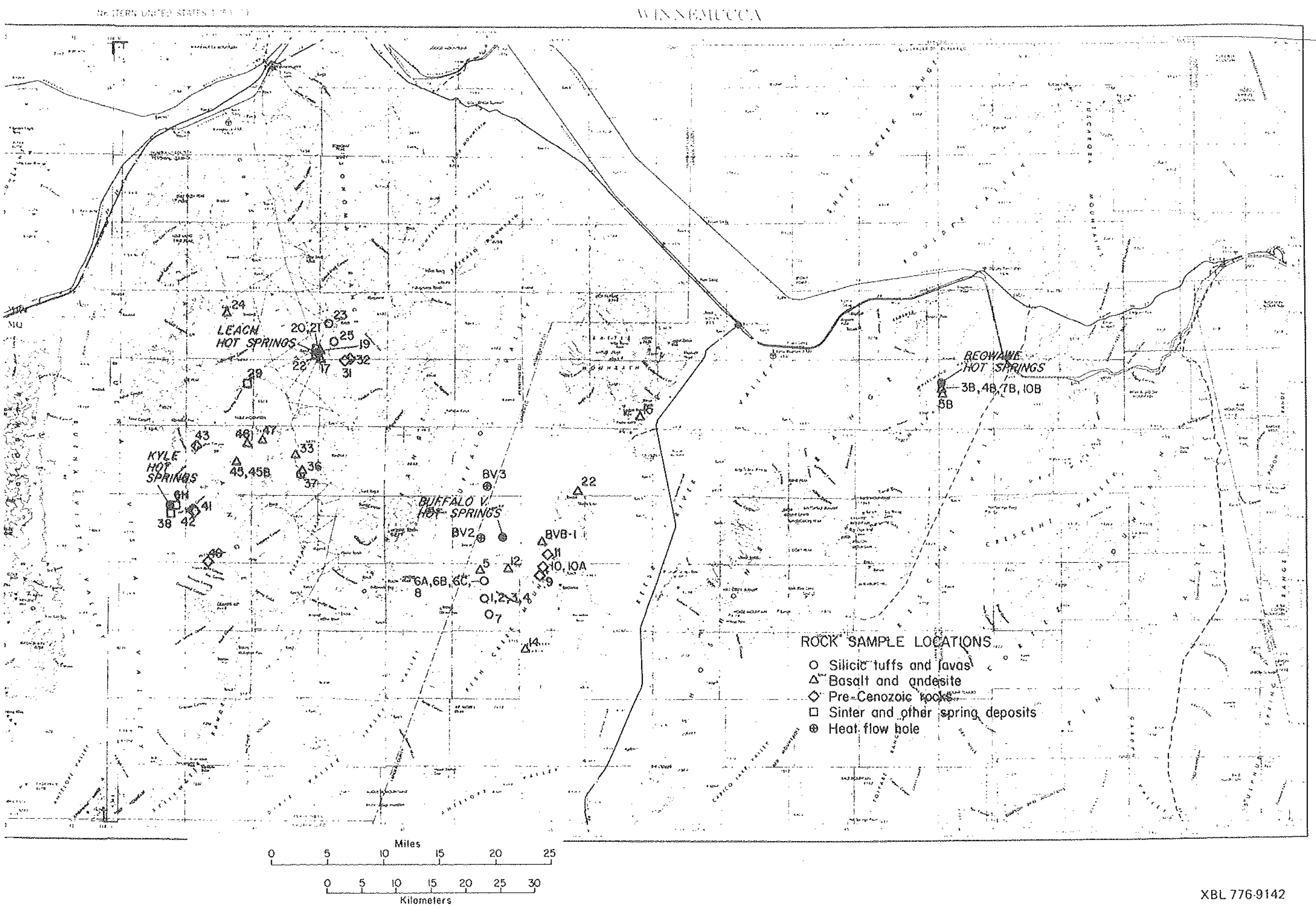

Figure 3. Rock sampling sites for Beowawe, Buffalo Valley, Leach, and Kyle hot springs.

7×10^8 metric tons at Kyle. Combining this information with the apparent ages of the spring systems (3.1×10^5 years for Leach and 7.8×10^4 years for Kyle) as determined by radio-chemical techniques, and with the chemistry of the present-day warm waters, we estimated the steady-state flow rates over the life of the spring systems: Kyle, 178 liters/second; Leach, 80 liters/second. The flow rate at Kyle is tens of times the present-day surface discharge;[5] the steady-state flow rate at Leach is five times the observed surface discharge.[7]

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NORTHERN NEVADA INVESTIGATIONS: HEAT FLOW

H. A. Wollenberg and D. di Somma

Results of heat flow measurements in Grass Valley, Nevada, begun in 1975[1] were analyzed in 1977. Eighty-two drill holes ranging in depth from 18 to 400 m were drilled in 1975, 1976 and 1977 over an area of 200 km^2 near Leach Hot Springs. Temperature gradients were measured and thermal conductivities determined on samples of cores and cuttings from the holes. The resulting heat flow values and interpretations have been published in a recently issued USGS-LBL Open File Report.[2] The project was sponsored in part by DOE and in part by the U.S. Geological Survey.

Outside the immediate area of Leach Hot Springs, heat flow ranges from 1 to 6.5 heat flow units (1 hfu=10^6 cal cm^{-2} sec^{-1}). Within 2 km of the springs, conductive heat flow ranges from 1.6 to more than 70 hfu, averaging 13.6 hfu. Much of this conductive heat flow stems from the circulating convective hydrothermal system at depth. Along with the large thermal anomaly associated with the hot springs, two other anomalies with heat flows greater than 5 hfu were also discerned (Figure 1); one centered approximately 5 km southwest of the hot springs (the mid-valley anomaly, QH3), the other approximately 9 km SSE in the vicinity of Panther Canyon. As with the hot springs anomaly, the Panther Canyon anomaly, although it has no surface manifestation, is most likely associated with a convecting hydrothermal system localized by faulting on the western boundary of the Sonoma and Tobin ranges.

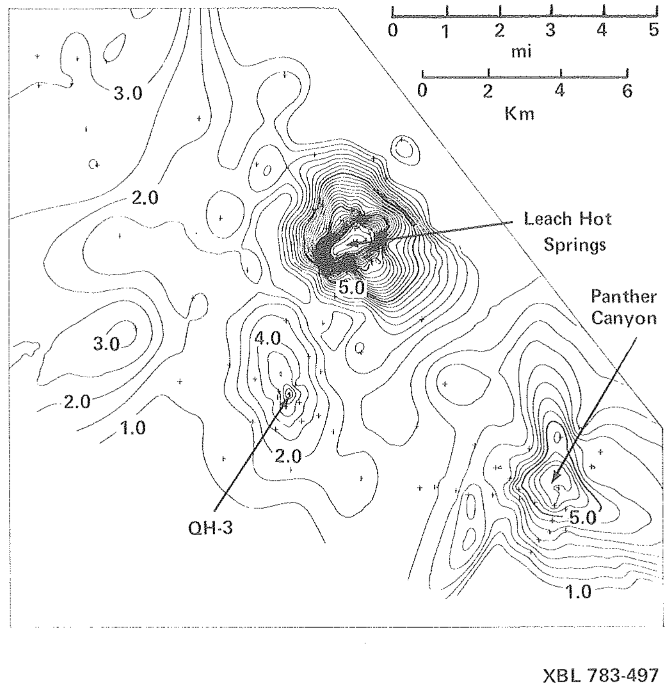

Figure 1. Contour map of heat flows from all holes, contour interval 0.5 hfu.

There is no apparent surface expression of the mid-valley anomaly either; it appears to be related to a bedrock high or horst, discerned by other geophysical measurements, buried beneath Quaternary alluvium and Tertiary sediments. Drilling in 1977 by the USGS[3] confirmed the presence of the horst and indicated that the observed high heat flow is caused by hydrothermal circulation in the bedrock.

Computer modeling to find the combined convection-conductive model fitting the Grass Valley heat flow data was undertaken by Majer.[4] His preliminary results generally support the proposed thermal model.

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NORTHERN NEVADA INVESTIGATIONS: GRAVITY STUDIES

N. E. Goldstein and B. Paulsson

Detailed gravity data from surveys made in the vicinity of Leach Hot Springs, Grass Valley, and Kyle Hot Springs, Buena Vista Valley, were analyzed. The results were then studied in relation to other geophysical and geological evidence to derive a better geological model of local structure and the gravity anomalies associated with heat flow highs.[1]

The complete Bouguer gravity data were interpreted by means of an iterative three-dimensional, two-layer inversion process to obtain the depth to "basement" beneath the valley-fill material. Basement in this sense is an interface which, for a density contrast that must be determined by trial and error, has zero depth at the range fronts and the correct value at points where there is subsurface information, for example, drill results. Supported by evidence from a deep U.S. Geological Survey drill hole in Grass Valley, a density contrast of 0.06 g/cm^3 was found to give a reasonable fit to the Paleozoic rock subcrop and the Paleozoic rock outcrop at the Sonoma Range. The depths to Paleozoic rocks were also found to agree very well with the seismic interpretation obtained by means of a finite element model of seismic reflection and refraction data along part of line E-E', Grass Valley.[2] Gravity and seismic interpretations also give very close agreement on the location and dip of the Hot Springs fault. The gravity interpretation was compared to resistivity models obtained from dipole-dipole measurements on two lines. In general, the gravity interpretation agrees reasonably well with the configuration of the 150 ohm-m basement,[3] although the electrical basement is usually 200 m to 400 m deeper than the density and velocity interface. This could be due in part to resolution and nonuniqueness problems in the resistivity interpretation.

The Grass Valley gravity inversion reveals a complex basement picture which was interpreted in terms of numerous inferred normal faults, some of which have surface expressions. Inferred faults trend mainly north-south and northwest-southeast, but there is also a set of northeast-southwest trending faults. The latter are interesting because they not only conform to the regional trend of hot springs in northwestern Nevada, but two of them are associated with local thermal anomalies. The Hot Springs fault passes through Leach Hot Springs and there is an unexplained 6 hfu thermal anomaly near the Panther Canyon fault, at the mouth of the Canyon. We can speculate that the intersection of older northeast-trending faults and the younger Basin and Range faults may provide the fracture permeability for ascending thermal waters.

Two local gravity highs, both associated with heat flow anomalies, were analyzed. Excess mass calculations for a 5 mgal residual anomaly centered at Leach Hot Springs gave an excess mass of 2.5×10^8 metric tons, believed due mainly to precipitated silica, and an excess density of about 0.18 g/cm^3. This is equivalent to a silicified pipe 1 km in diameter and 1.9 km in depth extent. This vertical dimension seems sufficient to explain the 100 ms P-wave advance at Leach Hot Springs,[2] but joint modeling of gravity and seismic delay data has not been done.

The smaller Section 14 gravity anomaly in T. 31 N., R. 38 E. was not studied in detail as it was believed to be caused by a shallow basement high, possibly fault controlled, extending northward from the Goldbank Hills. The coincident 5 hfu anomaly has a convective component, as determined from drilling.

Gravity data from Buena Vista Valley were processed in a similar manner. A density contrast of 0.06 g/cm^3 gave a zero depth-to-basement that conforms closely with outcropping Mesozoic-Paleozoic rocks of the East Range. Over the valley, the depth-to-basement agrees well with the 50 ohm-m electrical basement determined from a model study of dipole-dipole resistivity data.[3] A bulge in the gravity contours 2 km south of Kyle Hot Springs suggested a densification from precipitating $CaCO_3$, the principal deposit found at Kyle Hot Springs. A careful subtraction of the background gravity produced a broad 2 mgal local residual anomaly. The anomaly shape suggests it may be localized by northeast and northwest-trending faults, similar to the fault directions at Leach Hot Springs. The excess mass calculated for the anomaly is approximately 7.0×10^8 metric tons, nearly three times larger than the excess mass for the Leach anomaly. On the other hand, the age of the Kyle system, determined from radioelement abundances,[4] is approximately 78,000 years, considerably less than the age determined for the Leach system. This implies that the average flow rate within the Kyle system must be considerably greater than the flow rate within the Leach system. Part of the difference in mass can be attributed to the fact that the total dissolved solids in the Kyle discharge waters is five times greater than at Leach.[4] Nevertheless, the evidence suggests that the Kyle system may be more active and more promising as a geothermal resource than Leach.

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NORTHERN NEVADA INVESTIGATIONS: EXPLORATION STRATEGY ANALYSIS

N. E. Goldstein

An analysis and summarization of the many LBL geoscience investigations in northern Nevada was done to develop an exploration strategy helpful to industry. The LBL principal investigators (N.E. Goldstein, H.A. Wollenberg, H.F. Morrison and T.V. McEvilly) and University of California graduate students and staff (A. Dey, E. Majer, H.F. Beyer) evaluated the effectiveness of exploration techniques applied by LBL, plus some that were applied by others (Table 1). A quantitative "cost-effectiveness" rating was assigned for each technique, based on the ratio of effectiveness and cost. Effectiveness was quantified in terms of two parameters: (a) the scientific value of a technique, that is, whether interpretable information could be obtained, and (b) the practical value of the technique, that is, whether the results were helpful in answering geological questions about the thermal regime and the potential of the geothermal resource, or in planning follow-up exploration.

Based on the effectiveness ratings and discussions among investigators, an exploration plan was devised (Figure 1) consisting of:

1. Reconnaissance phase - directed at an initial study area of approximately 2500 mi^2. This phase would have a basic program of geologic studies, rock age dating, geochemical studies, color/color IR photography, low-sun-angle black and white photography, and an optional supplemental program consisting of regional seismotectonic studies and thermal IR imaging.

Table 1. Northern Nevada geothermal exploration plan outline.

	Reconnaissance Phase	Detail Phase	Drill Tests
Study Area:	2500 square miles	<100 square miles	2 to 4 square miles
Objective:	Reduce study area to one or more subareas of <100 square miles for detailed exploration	Reduce study area to one or more subareas of 2 to 4 square miles for drill tests	Verify the presence of geothermal resource
Methods:	A. Airborne ** Aeromagnetics ** Infrared imagery ** Photography ° Low-medium altitude color and color IR ° High altitude black and white	A. Airborne High sensitivity aeromagnetics	Test drilling to depths of 1 to 2 km and well logging.
	B. Surface * Geological studies * Geochemical studies * Regional gravity ** Rock age-dating * Passive seismic ° Regional seismotectonic studies ° Microearthquake and ground noise studies ** Hydrologic studies Regional magnetic variometry * Heat flow	B. Surface * Geological studies * Magnetics * Gravity * Active seismic * Passive seismic ° Microearthquake ° Teleseismic P-wave studies ° Ground noise * Resistivity studies * Self-potential * Heat flow	

* Data acquired directly by LBL or with the assistance of the U.S. Geological Survey.

** Data made available to LBL from other sources or from previous scientific studies in northern Nevada.

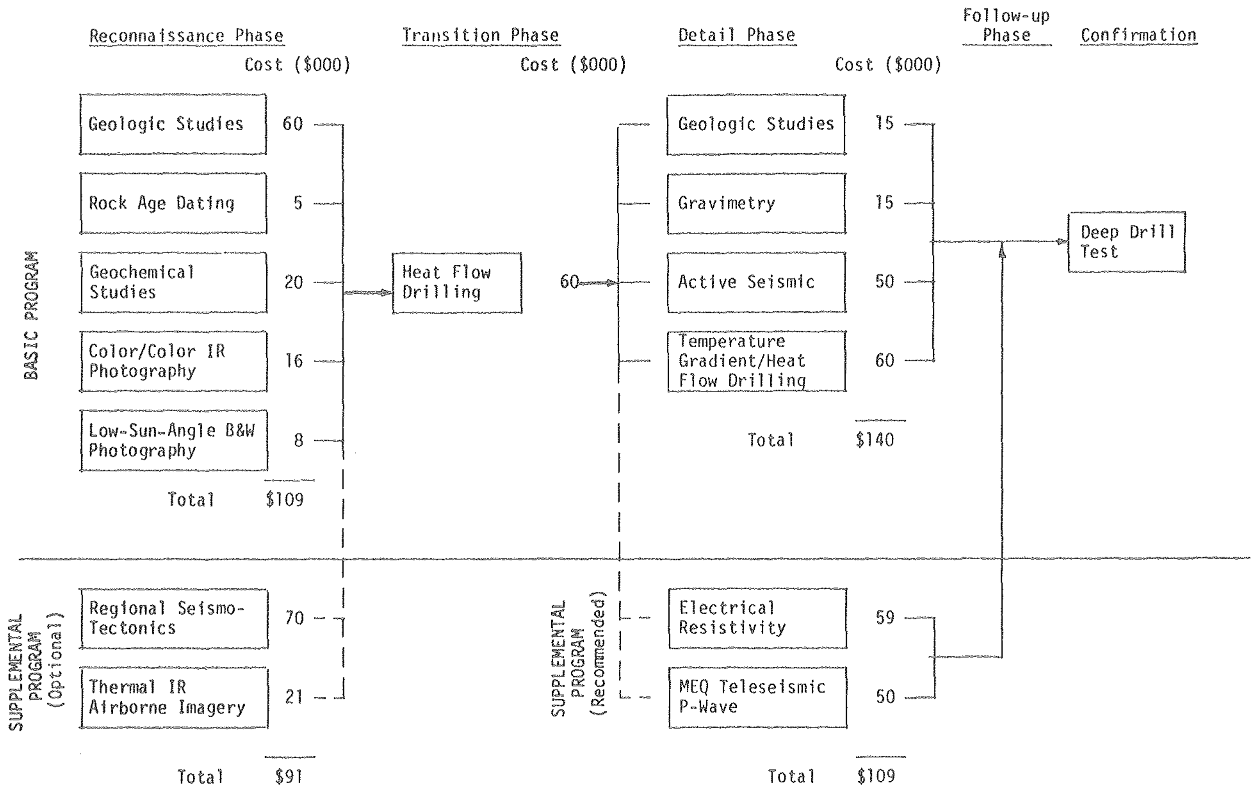

Figure 1. Northern Nevada geothermal exploration strategy.

2. Transitional phase of 12 heat flow holes drilled to about 500 feet, to supplement existing regional data.

3. Detail phase directed at a study area of approximately 100 mi^2. This phase would have a basic program of geologic studies, gravimetry, seismic reflection and refraction, temperature gradient/heat flow drilling, and a recommended supplemental program of electrical resistivity and microearthquake, teleseismic P-wave delay and amplitude variation studies.

4. Confirmation phase of deep drilling to test the targets outlined from previous work.

An exploration plan must be evaluated in terms of the success or failure of the deep confirmatory drilling. However, as this phase was not reached in the LBL program, the strategy must be considered preliminary and subject to verification.

The strategy developed was closely analyzed at critical phases to determine how variations at these phases would affect total outcome. The most important variables were (a) the timing of land acquisition and (b) the elimination of either or both the basic and recommended segments of the detail-phase exploration prior to confirmatory drilling. Many possible modes of action concerning these variables were studied by means of a decision tree analysis using chance probabilities based partially on experience. Each branch was followed through to either a successful drill test or a failure situation. From these studies, several important exploration guidelines were derived:

(a) Conducting the detail-phase exploration prior to land acquisition will result in a higher cumulative exploration cost, but will improve the chance for locating a favorable drill hole (by a factor of 2.2) if the project gets to the final drilling stage.

(b) Project cost-effectiveness is found to increase as exploration thoroughness increases. Deferring land acquisition until after the basic detail-phase exploration is completed gives higher cost-effectiveness values for both the general project and for those projects that ultimately reach the confirmatory drilling stage.

(c) An expected value (EV) analysis shows that the maximum return on drilling investment can also be expected if land acquisition is deferred until after the detail-phase exploration is completed. Conducting the recommended supplemental detail exploration prior to land acquisition entails the highest financial risk, but also gives the highest EV. Acquiring land before doing a more limited version of the supplemental detail exploration requires a lower financial risk and slightly higher cost-effectiveness but gives a lower EV.

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4. UNDERGROUND NUCLEAR WASTE STORAGE

The waste isolation program began in 1977 as a modest effort to study radioactive storage in crystalline and argillaceous rocks, investigate extant dry mines in the United States, initiate a material property testing program, and perform numerical modeling. In mid year, these projects were overshadowed by the initiation of a heater project in Stripa, a mining community near the town of Storå, Sweden by DOE and the Swedish government. By the end of the year, a second heater project was being initiated on the Hanford Reservation near Richland, Washington.

Most of the initial waste isolation studies have been merged into the heater studies or terminated. The equipment developed by the material property testing program is proving to be valuable for the heater projects. The numerical modeling program served as an excellent base for the co-operative heater project and was therefore merged into it. Results of its calculations are reported herein. The study of existing underground mines for storage potential developed unforeseen problems of a non-technical nature. The study was terminated at the request of the Office of Waste Isolation (OWI).

The heater project on the Hanford Reservation has just begun and is not therefore the subject of a report. Though details are still being developed, the project will generally be similar to the cooperative heater project between Sweden and DOE.

All remaining activities of the waste storage program are reported below in the form of summary reports on the project in general, and topical reports discussing project results.

AN APPRAISAL OF HARD ROCK FOR POTENTIAL UNDERGROUND REPOSITORIES OF RADIOACTIVE WASTES

N. G. W. Cook

INTRODUCTION

For more than three decades, large quantities of radioactive waste have been stored at a number of surface sites, and the quantity is increasing each year. Though every precaution is taken to protect the environment from the adverse effects of stored nuclear wastes, surface storage does not appear to be an effective or practicable long-term solution. Even the most carefully managed surface storage may not be adequately secure against events such as major meteorological or geological disasters, acts of terrorism, war and political turmoil.

Archaeological and geological experience provides cogent evidence that subsurface burial gives long-term protection to a wide variety of different objects against disasters such as those mentioned above, amongst others. Accordingly, it is logical to explore the feasibility of using appropriate underground storage for the effective isolation of radioactive wastes. One important aspect of this feasibility study concerns the safety and stability of the excavations made for use as repositories. The underground mines in existence, some for more than a century, can be used to provide initial information on safety and stability. Furthermore, a wealth of experience exists concerning the design and construction of underground excavations for civil and mining engineering purposes. In the 18 countries of the Organization for Economic Cooperation and Development (OECD), this involves the annual construction of the order of 50,000 km of tunnels alone.[1] This experience covers most kinds of rocks in virtually every terrain and climate, beneath land and water, and down to depths approaching 4 km below surface.

The overall study would require an examination of the potential effects on such excavations of the virgin state of stress in the rock, the stability of, and interaction between, adjacent excavations and the consequences of heating of the rock by the radioactive decay of the waste. In this report, these questions are addressed in general terms.

THE VIRGIN STATE OF STRESS IN THE ROCK

In general the vertical component of the virgin state of stress in rock has a value close to that given by the weight of the overburden. Exceptions to this are areas of uneven topography at depths that are shallow compared with the relief, or in and close to inclusions and intrusions of rock with differing mechanical properties from the surrounding rock.

A significant number of attempts has been made to measure the complete virgin state of stress in rock at different locations and depths throughout the world. These measurements have shown that the values of the horizontal components of this state of stress range from about a third to three times that of the vertical component. A compilation of many of these measurements has been done by Hoek and Brown,[2] and is shown in Figure 1. From this it can be seen that relatively high values of the horizontal components of stress tend to be a shallow phenomenon, possibly associated with the effects of rapid denudation.[3]

The value of the vertical component of rock stress is, on average, some 2.7 times greater than the hydrostatic head of water at the same depth, that is, the value of the ratio of the hydrostatic

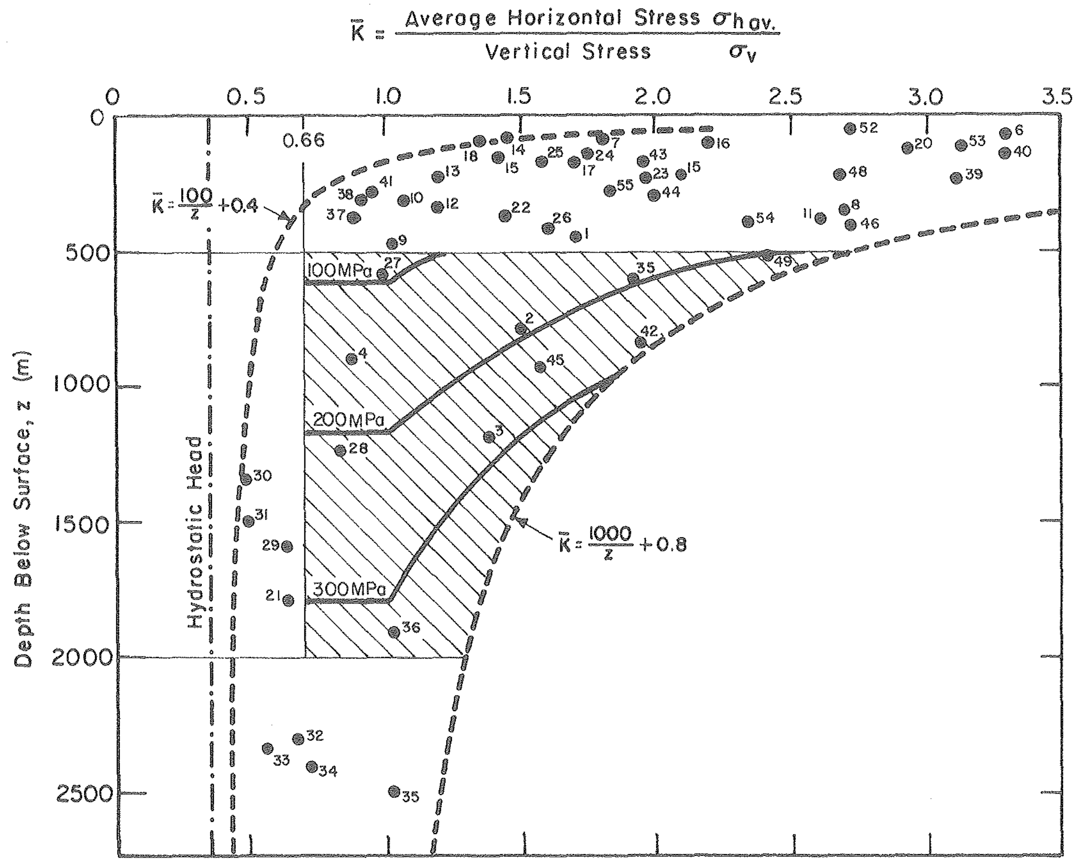

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Figure 1. The ratio between measured values of the average of the horizontal components and the vertical component of the virgin state of stress as a function of depth. The hatched region between 500 m and 2000 m below surface represents those states of stress which would preclude faulting and diminish the ingress of groundwater. The contours marked 100 MPa, 200 MPa and 300 MPa define those parts of this region within which it is considered safe to place a repository if the uniaxial compressive strength of the rock has these values.[2]

head to the vertical stress is 0.37, as is illustrated also in Figure 1. This is a result of the ratio between the average density of rock and that of water.

For many reasons, the preferred depth of an underground rock repository for the storage of radioactive waste is likely to be in the range from 0.5-2 km below surface. Within this range, the virgin state of stress in the rock at any potential repository site should meet three criteria:

1. The value of the minimum horizontal component of this state of stress should be significantly greater than that of the hydrostatic head of water at the same depth. Otherwise, such near vertical joints and cracks as exist in the rock may not be tight against groundwater or could be opened by the pressure of its hydrostatic head.

2. The ratio between the values of maximum and minimum components of this state of stress should be relatively small, so as to obviate the likelihood of faulting, even in the presence of hydrostatic water pressures.

3. The maximum stress difference should be less than some safe value. An argument can be made for limiting this stress difference to 25 MPa.

Assuming that the value of the vertical component of the virgin state of stress is either the maximum or the minimum principal stress and that the values of the horizontal components are comparable, that portion of Figure 1 falling within the criteria described above is delineated and shown hatched.

THE STRENGTH OF ROCK AROUND EXCAVATIONS

Underground excavations can have many different configurations. In mining, these are dictated largely by the desire to extract a relatively high proportion of the ore. In civil engineering, large equipment must often be accommodated. Neither of these requirements seems to be important in laying out the excavations for an underground repository of radioactive wastes. Probably the most important consideration in this case is the safety, stability and security of the excavations. In general, therefore, such excavations are likely to take the form of a series of adjacent but more or less independent tunnels. This results in simple, safe excavations with a high degree of isolation between each tunnel.

It is necessary to form some idea of the magnitude of the effects that size and geological discontinuities have on the strength of hard rock, in order to evaluate the rock's potential as an underground repository of radioactive wastes. Some guidance may be gained from an examination of the values of the field stresses known to have caused damage to tunnels in hard rock. Cook[4] showed that failure by slabbing of the sidewalls of tunnels about 3 m^2 occurred when the major component of the field stress to which these tunnels were subjected reached a value of between 0.15 and 0.30 times the uniaxial compressive strength of laboratory specimens. This suggests that the most likely ratio of major field stress to uniaxial compressive stress, at which failure around such a tunnel becomes apparent, is 0.18, and that this ratio increases as the strength of the rock decreases.

In the absence of any better information, assume that a safe value for the ratio of the field stress to the uniaxial compressive strength is 0.15. Those regions of Figure 1 where tunnels could be safely sited in rocks with uniaxial compressive strengths of 100 MPa, 200 MPa, and 300 MPa are shown by the relevant contours. From these it appears that the uniaxial compressive strength of the rock at a suitable site probably should be at least 200 MPa.

THERMOMECHANICAL EFFECTS

Short-Term Local Phenomena

The thermally-induced stresses around point and line sources, and around a borehole 40 cm in diameter, have been calculated for times of 15 days and 90 days using properties typical of hard rock. A period of 15 days is sufficiently short so that the temperature field and the stresses associated with it are distinctly transient in character, but at 90 days these are closely approaching their steady-state distributions.

The sums and differences of these calculated stresses have been plotted in Figure 2 where they are compared with a plot of the Coulomb criterion for the strength of a typical hard rock. From this figure it can be seen that the thermal stresses produced by a source of 1 kW power are well below the strength of the rock. Even if the power output were increased by several fold only the stresses on the wall of the borehole would approach the failure criterion. Failure of the borehole wall is not likely to damage a well-designed canister but would make its retrieval difficult. Accordingly, it seems prudent to consider casing boreholes.

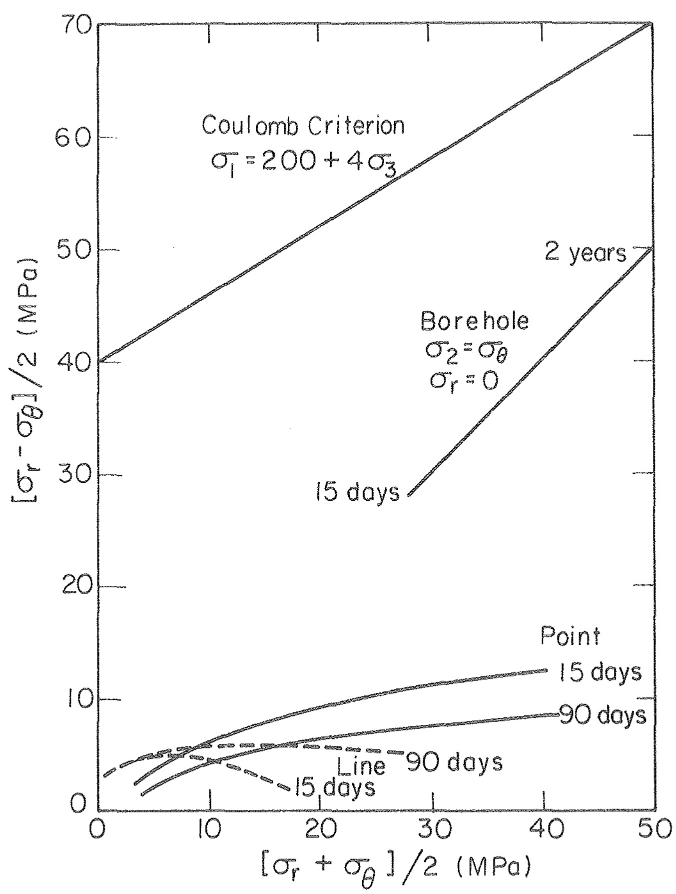

Figure 2. A Mohr diagram comparing the average values of the differences and sums of the principal thermally-induced components of stress around line (400 W/m) and point (1 kW) heat sources at 15 days and 90 days, and the axial and tangential components of stress on the wall of a borehole, with the strength of a typical hard rock.

Long-Term, Regional Phenomenon

In the previous section, the short-term effects of heat flow from individual canisters have been evaluated. At some time, the temperature fields between adjacent canisters will interact to significant extent. At this stage, the local effects become less important than the overall flow of heat into the surrounding rock from the whole array of canisters in a repository.

Most concepts for underground repositories involve one or more near plane horizons of excavations, within which the canisters are contained. As the lateral dimensions in this plane are envisaged to be of the order of a kilometer, the long-term heat flow can be approximated as one-dimensional flow into the surrounding rock mass normal to this plane. Important questions which must be examined concerning this heat flow are the temperatures on the horizon of a repository as a function of the waste canister density, and the heat flow into the surrounding rock as a function of time.

Reprocessing used fuel produces high-level waste whose characteristics provide some guidance to the thermal characteristics of wastes that are likely to be isolated in a repository. The decline in power output of a standard canister of high-level waste becomes significant in the long term. It is convenient that this characteristic can be approximated closely by the power output of a plane, isothermal heat source.[5] Using the standard equations for linear heat conduction,[6] and remembering that heat flows away from a repository both upwards and downwards, Table 1 has been prepared to show the power densities for different temperatures of the repository horizon and the corresponding areas required by each high-level waste canister at 20 years after reprocessing (assuming that they are cooled for 10 years before burial).

Using the same equations, the distances away from the plane of the repository, to which the isotherms representing 50, 25 and 10 percent of the source temperature migrate as a function of time, have been calculated. These are given in Table 2.

These data show that the heat released by the decay of the wastes migrates only a relatively small distance away from the plane of the repository even over long periods of time; this justifies the use of one-dimensional heat flow in the analysis. The data also show that it is practicable to consider a repository with a number of horizons separated by a normal distance of 200 m. A single repository with 3 horizons, each with a total area of about 5 km^2 and separated by about 200 m, appears to have the capacity to store waste with power output of 240 MW at 10 years after burial.

Table 1. The average power density for a planar repository at 10 years after loading and the corresponding area required for each canister with a power output of 1.7 kW at 20 years after reprocessing for different temperatures of the repository horizon.

	Repository Temperature (°C)			
	50	100	200	300
Power density (W/m^2)	7.9	15.8	31.6	47.4
Area per H.L.W. Canister(m^2) (1.7 kW at 20 years)	220	110	54	36

Table 2. The normal distance away from a planar repository to which the isotherms representing 50, 25 and 10 percent of the source temperature migrate as a function of time.

	Time (years)	12.5	25	50	100
Distance (m)	50 percent	19.6	27.6	39.1	55.0
	25 percent	32.5	46.0	65.0	92.0
	10 percent	47.5	67.0	95.0	132

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COOPERATIVE WORK PROGRAM WITH SWEDISH NUCLEAR FUEL SUPPLY COMPANY ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS

P. A. Witherspoon, N. G. W. Cook, J. E. Gale, C. A. Brown, P. Kurfurst, M. McEvoy, C. H. Amick, C. F. Tsang, M. Hood, P. H. Nelson, T. Doe, and K. Mirk

INTRODUCTION

The cooperative work program between Sweden and the United States was first discussed at an OWI-sponsored workshop on "Movement of Fluids in Largely Impermeable Rock," held January 27-29, 1977 in Austin, Texas. There, representatives of Kärnbränsekerhet (KBS, Swedish Nuclear Safety Program), an affiliate of Svensk Kärnbränsleförsorjning (SKBF, Swedish Nuclear Fuel Supply Company), indicated that an abandoned iron ore mine in Stripa, Sweden was available for field investigations on the general problem of underground storage in a non-salt formation. Detailed plans were presented to KBS and SKBF in late spring, 1977 and after an amendment to a 1966 agreement for peaceful uses of atomic energy was signed on July 1, 1977, the project got under way officially.

OBJECTIVES

The successful use of mined caverns as waste repositories depends on isolating the radioactive materials from the biosphere for long periods of time. In effect, this means selecting a rock mass where the only practical pathways for fluid movement through such fractures will be essentially nil. To be able to make such a finding requires a number of specialized field investigations on the various factors that control water movement. Thus, the principal object of the cooperative research project at Stripa is to determine, to some measurable degree of certainty, how well we can predict the response of a real rock mass to high thermal loading. Corollary objectives are:

1) to conduct large scale field experiments in granite for the purpose of establishing design parameters for waste repositories in hard rock and making safety assessments for such facilities,
2) to develop new instruments and techniques that are capable of producing the required data and techniques despite the hostile environment that results from high temperatures over a long period of time,
3) to collect experimental data necessary both for the development and validation of predictive models, and
4) to promote the international exchange of information and idea.

To achieve these objectives, the LBL participation in the Swedish-American cooperative work program has been organized into three main activities: 1) full scale heater experiments, 2) time scale heater experiments, and 3) fracture hydrology. Additionally there are support activities consisting of 4) geophysical assessment of fractured rock masses, 5) laboratory measurement of material properties, 6) measurement of mass transfer of water to the ventilation system, and 7) measurement of in situ stresses by hydraulic fracturing.

1) Full Scale Heater Experiments to Investigate the Effects of Temperature Increases in Crystalline Rocks

The objective of this task is to investigate, over a two-year period, the temperature effects in crystalline rock of full scale heaters that simulate the energy output of radioactive waste canisters.

The objective calls for canisters, 3 m in length and 0.3 m in diameter, containing heater elements to be designed, constructed and emplaced in vertical holes at the Stripa mine. The canisters are designed so that the power output of one of these heaters can be adjusted to 5 kW to represent the typical power level of reprocessed fuel after three years and the other canister will have a power output of 3.5 kW to represent similar waste products approximately five years old. The objective further calls for the rock mass adjacent to the canisters to be monitored by means of thermocouples for rock temperatures and by means of 30 extensometers, 30 borehole deformations, USBM gauges, and vibrating wire IRAD gauges, to measure displacements.

The objective entails a second full scale experiment phase involving the placement of a ring of eight small, one-kilowatt heaters in a 0.9 m radius around the 5 kW canister-heater unit to evaluate sequential heat loadings.

2) Time Scaled Heater Experiment to Assess Long-Term Effects of the Thermal-Mechanical Loading on a Repository in Crystalline Rock

The objective of this task is to obtain meaningful data within a two-year experiment to corroborate and validate theoretical analyses of the effects of thermal-mechanical loading of a repository in crystalline rock during the critical time period of 10 years to 100 years of operation.

Because it is impractical to check the effects of total thermal loading on a rock mass in the critical period from 10 to 100 years, this objective can be achieved with a time-scaled experiment in which times will be compressed in the ratio of 1:10, that is, two years of time scale experiments will yield 30 years of data from full scale heater performance. To accomplish this, the linear scale is reduced to $1/\sqrt{10} \cong 0.32$ of the full scale. Thus, to facilitate the objective of this task, an array of eight scaled heaters with an initial power output of 1 kW will be placed in the Stripa mine in such a way that a three-dimensional pattern of thermal interaction between the heaters and surrounding rock is expected to occur within a few months from the start of the experiment.

The task objective additionally calls for the measurement of decrepitation, or spalling, of the heater holes and the use of five extensometers with their associated thermocouples plus 60 thermocouples to monitor rock temperature and behavior in the rock surrounding the heater holes.

3) Assessment of Fracture Hydrology

The objective of this task is to define the surface and subsurface hydrological conditions of the fractured granite rock mass at Stripa as a function of time and temperature using various borehole tests. Accomplishment of this objective necessitates 1) defining the geometrical properties of the fracture system, b) determining the distribution of fluid pressures and permeabilities associated with this system, c) collecting and analyzing samples of groundwater from various parts of the rock mass, and d) analyzing the above data to provide a coherent description of the nature and magnitude of the groundwater flow in the vicinity of the underground openings. Achievement of these results calls for the development of new borehole tools and new methods of data collection and analysis.

4) Geophysical Assessment of Fractured Rock Masses

The objective of this support task is to determine the applicability of different surface, subsurface and borehole geophysical techniques in delineating and characterizing the fracture system in the granite body at Stripa. To facilitate the objective, three other support tasks have been defined based upon the scale of the measurement and the techniques employed: 1) borehole measurements on the scale of one meter, done with tools in a single borehole; 2) cross-hole measurements on the scale of tens of meters, done with tools in different boreholes or with arrays in a single borehole; and 3) surface measurements on the scale of hundreds of meters, done with surface survey equipment.

5) Laboratory Measurement of Material Properties

The objective of this support activity is to measure the material properties of carefully selected rock samples from the granite rock mass at the Stripa mine. Material property measurements are needed in understanding the hydraulic, thermal and rock mechanic behavior of the fractured rock mass. This objective calls for the drilling of oriented core samples for unfractured rock and rock containing natural fractures. Additionally, a large rock core sample of approximately 1 m in diameter is to be tested for changes in fracture permeability as a function of axial stress and fluid pressure change.

6) Mass Transfer of Water to the Ventilation System

The objective of this task is to determine the gross seepage rate in the low permeability granite rocks at the Stripa mine. This necessitates isolating a portion of the tunnel and monitoring the difference in humidity between air forced into and flowing out of the tunnel, enabling the detection of minute seepage not ordinarily discernible through the rock mass on a large scale.

7) Measurement of In Situ Stresses by Hydraulic Fracturing

The objective of this activity is to determine the virgin state of stress in the fractured granite rock mass in the Stripa mine. Hydraulic fracturing will be employed to achieve the objective by obtaining measurements of in situ stress.

THE YEAR'S ACTIVITIES

Full Scale Heater Tests

Canisters containing heater elements were designed and constructed during fiscal year 1977 so that the dimensions of the canisters (3 m length x 0.3 m diameter) approximate the size of the container that is currently envisaged for use with reprocessed radioactive waste. Figure 1 shows a cutaway drawing of the two full scale heaters and some of the horizontal instrument holes that are being driven from an adjacent lower level drift.

Drilling of the instrumentation holes was more than 35 percent completed by the end of fiscal year

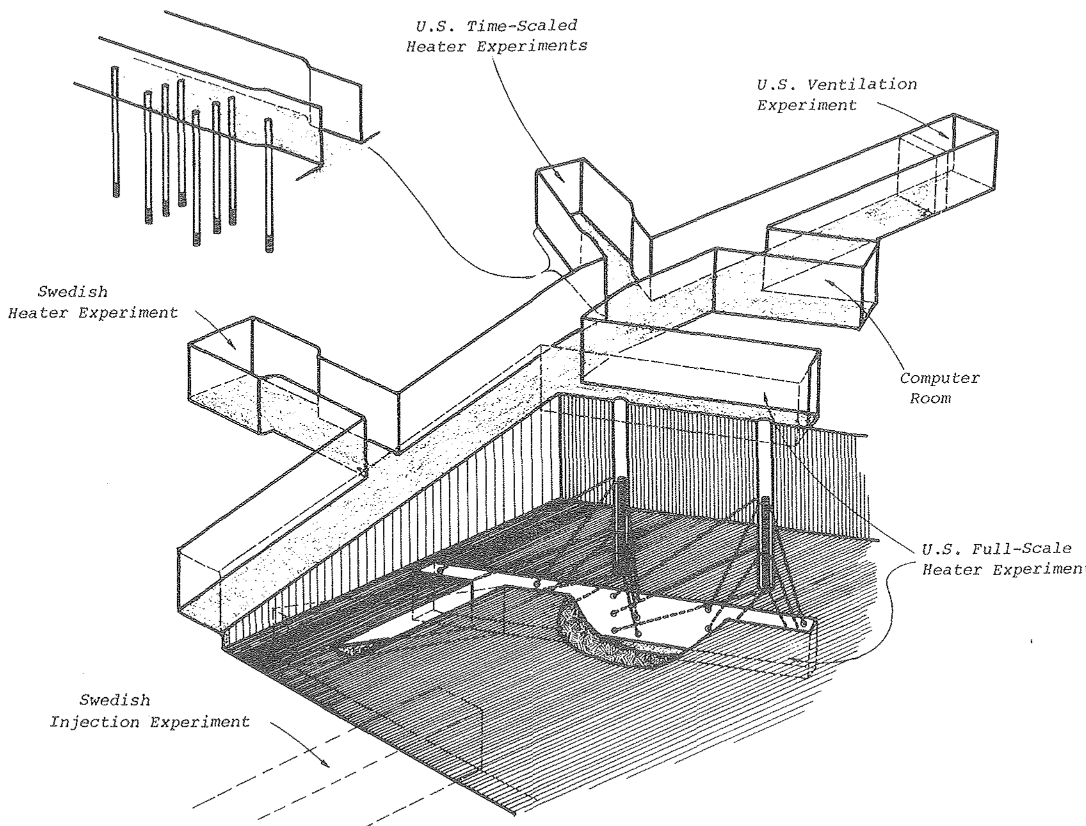

Figure 1. Graphic illustration of U.S. and Swedish experiments in the cooperative work program at Stripa.

1977 and mining operations for the extensometer drift were finished.

Time Scale Heater Tests

Calculations were completed during the design phase of the Swedish Cooperative program in fiscal year 1977 which show that thermal reaction interaction begins to occur between full scale canisters in a period of three years if the spacing between the canisters is 10 m. This is illustrated by the migration of the 30°C incremental isotherm over a period of one to ten years as shown in Figure 2.

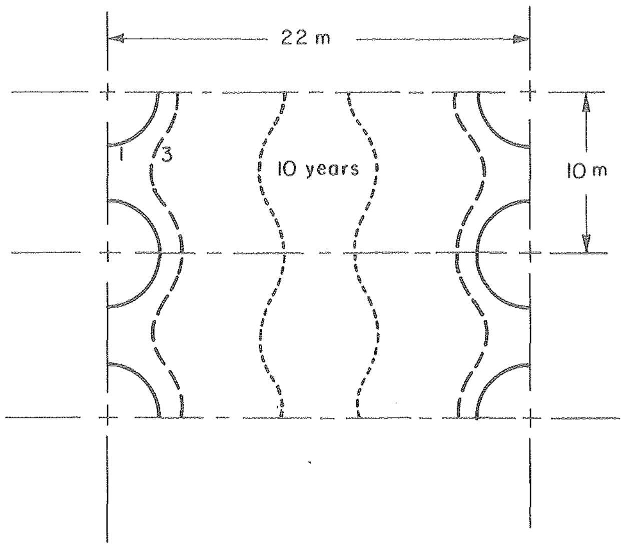

Figure 2. Thermal interaction of canisters for the 30°C incremental isotherm after 1, 3, and 10 years.

Heaters for Experimental Program

Three different types of heaters have been designed for the project in Sweden:

1. Main heater units for the full scale experiment. These are designed to simulate the actual size, and to give power outputs representative of canisters used for radioactive wastes.
2. Peripheral heaters for the full scale experiment. These are required to heat the rock mass surrounding one of the main heaters.
3. Heaters for the time scale experiment. These are designed to a linear rate 0.314 with an initial power output of 1 kW.

Additionally, a test facility was constructed in Berkeley so that all of the heaters could be tested and checked prior to their shipment to Sweden.

The main heaters for the full scale experiment have been designed with four 5 kW heater elements in each unit. The heaters are designed so that the units will be operated with power outputs of 3.5 kW or 5 kW which can normally be maintained by using only a quarter of the required power for the unit from each heater element. However, the design is such that should an element fail, the full power required by each unit can be supplied by one heater element only. Three heater units of this design have been constructed and were undergoing testing in the test rig which has been fabricated. Two of these units are illustrated in Figure 3 and the test facility is shown in the background. Tests with one of the heater units was completed during fiscal year 1977, running the unit at 600°C for a continuous period of five weeks. This unit, together with an untested unit of the same design, is shown in Figure 3.

The peripheral heaters for the full scale experiment were designed and manufactured in fiscal year 1977 and laboratory tests in the experimental rig will take place in early fiscal year 1978.

The design of the time scale heater units was under way at the end of fiscal year 1977 though it was yet to be finalized. A facility to monitor deformation of the boreholes in which these heaters are placed has been incorporated in the design of these units, and underwent laboratory testing in fiscal year 1977.

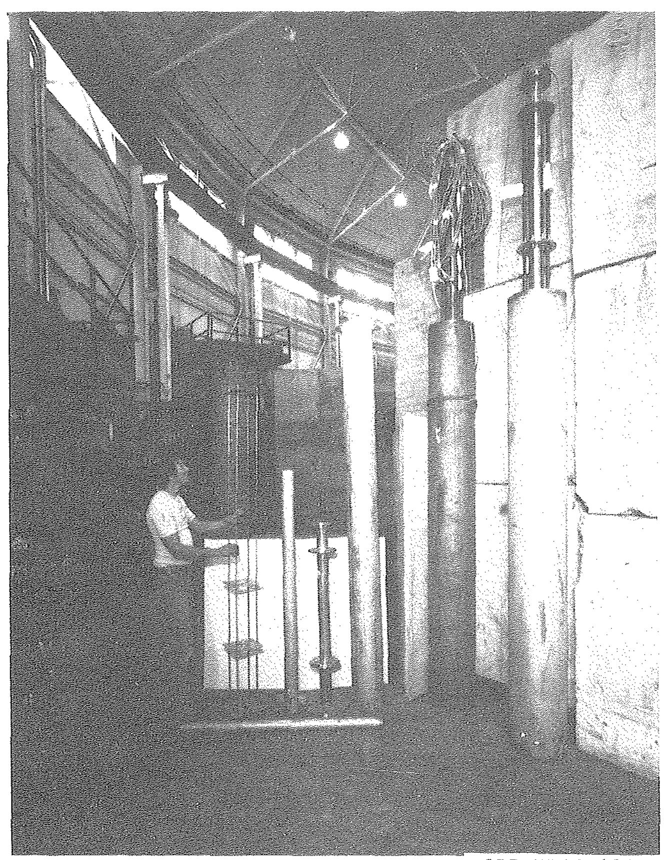

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Figure 3. Photograph of full-scale heaters and components with test stand in the background. Heater at second from right is shown after running five weeks at 600°C.

Instrumentation and Measurement Techniques

Three different types of instruments were modified and tested to monitor the displacements in a rock mass: 1) extensometers, 2) USBM gauges (high temperature model), and 3) vibrating-wire IRAD gauges (high temperature model). Testing and modification was still in progress and at the end of fiscal year 1977 the following was in progress or had been completed:

1) The thermal expansion of the extensometer invar rods was found to be higher than had been expected, which would have required many temperature readings along the length of the bar in order to determine the displacements of the rock to sufficient accuracy.

2) Super-invar was developed and found to have a much lower coefficient of thermal expansion than invar. Calculations have shown that four measurements along the length of a super-invar bar would be sufficient to determine displacements of as little as 25 μm in the rock. Calibration of the extensometers using this material with different thermal gradients applied along the bar is in progress.

3) A suitable grout capable of withstanding high temperatures has been selected.

4) Investigations were carried out to determine the time/temperature stability of the newly designed high temperature USBM borehole deformation gauges.

5) Testing of the vibrating wire, IRAD gauges at different temperatures and stresses has begun.

6) Development of a technique which would allow de-watering of the instrument holes after the instrument has been installed is in progress.

7) Cromel-alumel thermocouples have been selected for the numerous temperature measurements that are to be made.

A Mod Comp IV/25 computer has been selected to acquire, process, and display data during the full scale and the time scale experiments. Detailed plans for the connection of the instrumentation channels for analysis and display on the computer are shown in Figure 4. A substantial amount of theoretical analysis was carried out in fiscal year 1977 and an example of the temperatures calculated in the rock adjacent to the heaters for both full scale and time scale experiments is illustrated in Figure 5. This figure, which is hard copy from one of the two computer display units, shows the flexibility of the machine output.

Fracture Hydrology

Borehole equipment for pressure measurements, injection tests, and water sampling has been designed, constructed and shipped to Stripa for field testing. Some initial problems were encountered with the downhole pump assembly and these will be corrected in fiscal year 1978. At the request of the Swedish Geological Survey (SGU), the LBL borehole packer equipment was used successfully in assisting SGU scientists in making pressure measurements which were critical to the proper interpretation of hydrological information collected by SGU.

Detailed mapping of the fracture system was begun and carried out in cooperation with SGU. At the end of fiscal year 1977, the LBL staff was carrying out line sampling of the fracture data in selected areas, detailed mapping of fractures in the full scale and time scale rooms, and careful logging of fractures in the drill core from all instrument and heater holes.

By the end of fiscal year 1977, drilling had been initiated in two of the three oriented boreholes necessary for completing the picture of the fracture system in the granitic rock maps. All of the drill core has been reconstructed and logged. Both boreholes have been surveyed and camera-logged. Pressure measurements were made every 10 to 50 m during the drilling.

Water samples were collected at different depths within the deep borehole that was driven from the 410 m mine level and from a number of other locations. The samples are for analysis of gas content, water chemistry, isotope concentrations and field geochemical conditions.

The fracture system in the surface outcrops has been analyzed and a site selected for a vertical percussion hole (150 mm diameter) to be used in a program of pumping out tests for determining the average flow properties of the rock mass. Drilling was completed for four of seven shallow surface boreholes which will be used to monitor changes in water table levels that may occur.

Support Activities

As part of the geophysical assessment of fractured rocks, a portable logging system for the borehole measurements, which is capable of operation both underground and on the surface, was designed, specified and purchased in fiscal year 1977. Figure 6 shows the logging unit and the associated tools which include neutron (for water content), temperature, gamma-gamma (for rock density and fracture delineation) and natural gamma, a variety of electrical measurements, and caliper. A focused resistance log technique, developed by SGU for delineating fractures in the case of cross-hole measurements, has been incorporated into the US measuring scheme. An experiment to measure the effect of change in acoustic propagation in the thermally stressed rock mass was designed in fiscal year 1977.

A section of test tunnel has been designated for the measurement of ventilation mass transfer in order to determine the gross seepage rate in the low permeability, granitic rock mass. Otherwise, no work was planned in fiscal year 1977 for the support activities of Laboratory Measurement of Material Properties, Mass Transfer of Water to the Ventilation System, or Measurement of In Situ Stresses by Hydraulic Fracturing.

PLANNED ACTIVITIES FOR FISCAL YEAR 1978

The planned program for fiscal year 1978 is shipment of all the instrumentation, the computer and ancillary units to the Stripa mine in Sweden in early fiscal year 1978. Installation, testing and calibration of the equipment, instruments and

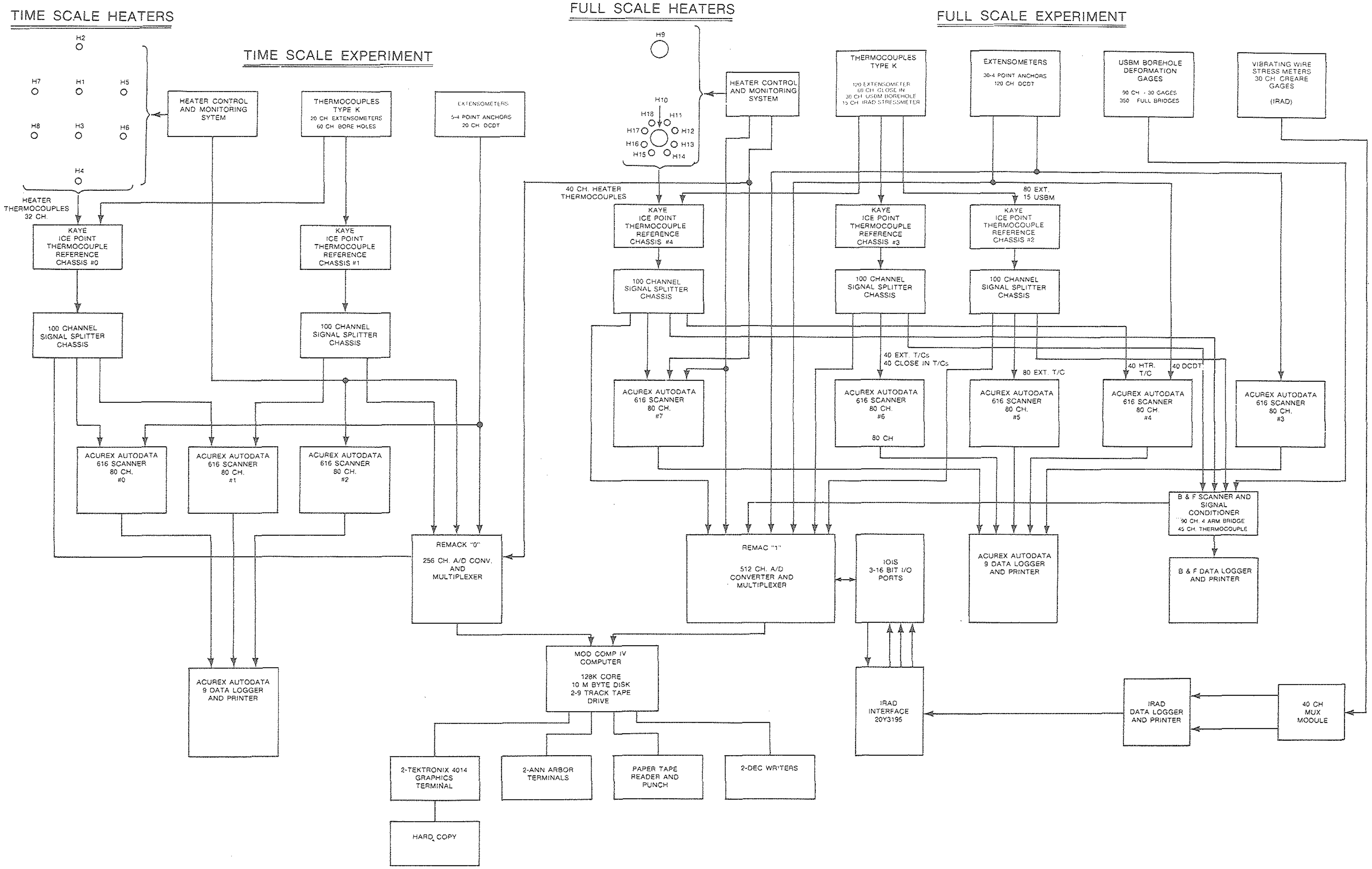

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Figure 4. Diagram of all instrument channels for full scale and time scale heater experiments showing input to Mod Comp IV computer with graphical display and hard copy.

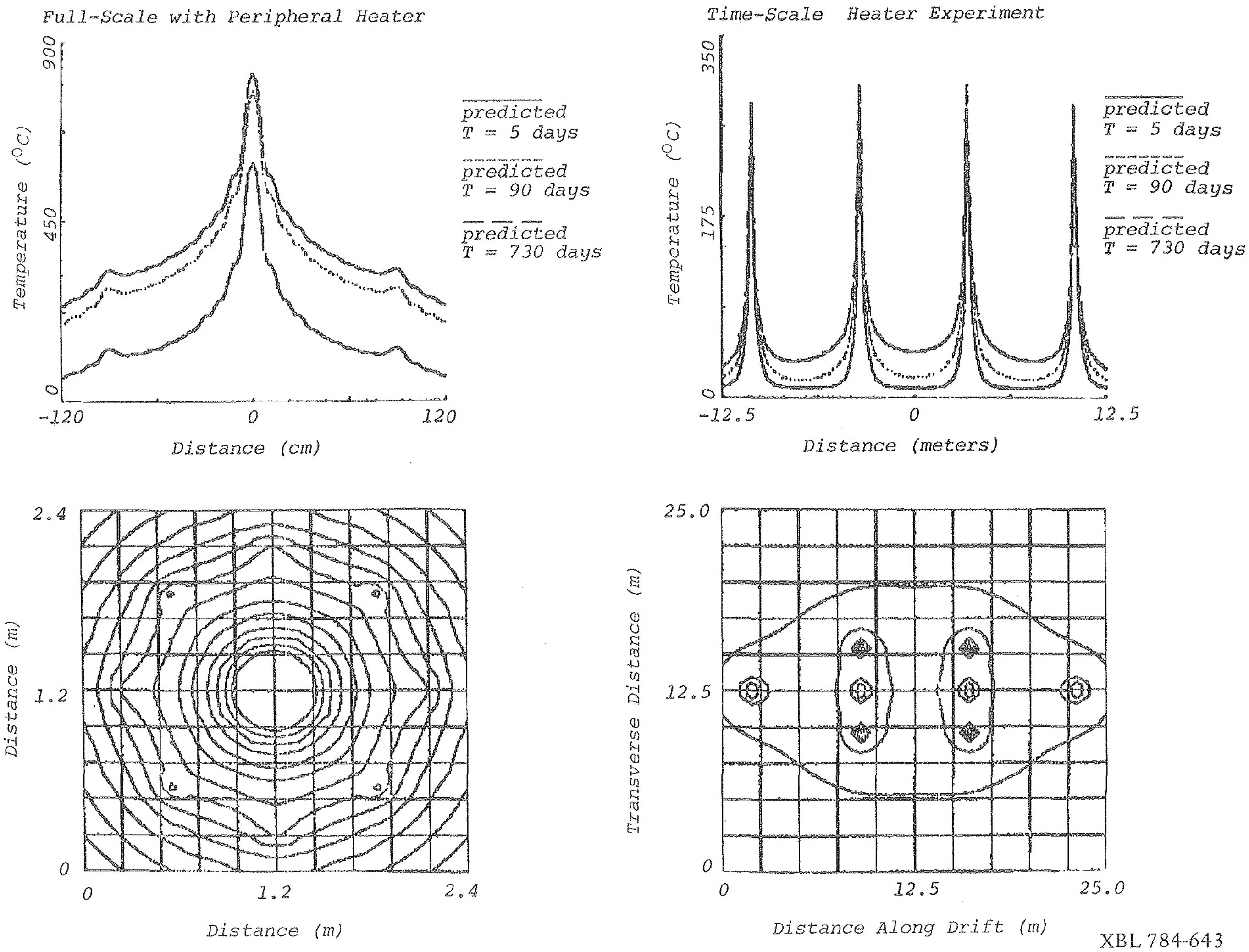

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Figure 5. Example of hard copy output from Mod Comp IV/25 computer. Left pair shows computed temperature for central region of full scale heater experiment; right pair shows time scale heater experiment.

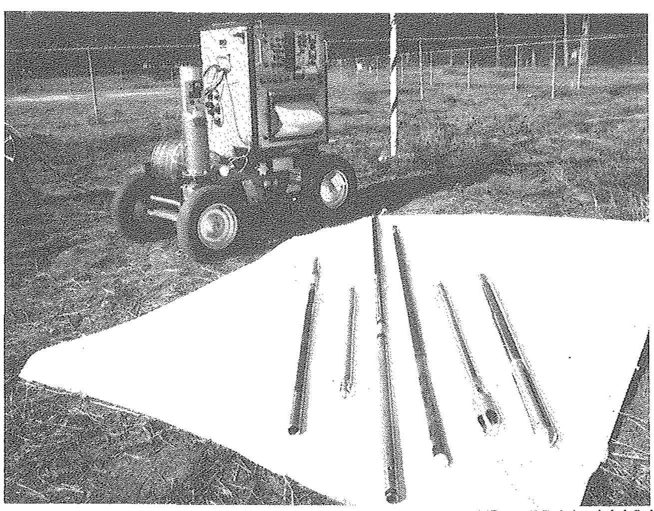

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Figure 6. Portable logging system for investigation of boreholes. From left to right the borehole instruments are neutron-thermal neutron, temperature, gamma-gamma, natural gamma/electrical, spinnter, and caliper.

the computer is scheduled to be completed by May 1978. At this point the experimental program will commence when the full scale heaters and time scale heaters are turned on. Significant data is expected from the time scale experiment by the end of fiscal year 1978.

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RADIOACTIVE WASTE STORAGE IN CRYSTALLINE AND ARGILLACEOUS ROCKS

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D. Snow, H. Amick, and T. Chan

INTRODUCTION

Crystalline and argillaceous rock have the characteristics that could support safe, economic, and environmentally feasible repository siting. These rock types have been given high priority in Canadian, Swedish, German and French waste storage research. LBL began in August 1977 to develop a research study plan that could guide in evaluating the utility of storing radioactive waste in repositories in crystalline or argillaceous rocks. Three other interrelated research tasks were also initiated: evaluation of in situ field studies of seepage in "dry" mines, laboratory investigations on ultralarge rock samples, and mathematical modeling studies of fluid flow in rock masses containing deformable fractures. Input from these four distinct, yet interrelated studies, will be synthesized and presented in a document titled, "Crystalline and Argillaceous Rock: Potential Repository Siting for Radioactive Waste Storage."

1977 AND 1978 ACTIVITIES

Geotechnical Assessment Study Plan for Radioactive Waste Storage in Crystalline or Argillaceous Rock

The study objectives are to assess the utility of storing radioactive wastes deep within crystalline or argillaceous rock (Figure 1). The study defines the state-of-the-art in terms of design, instrumentation, and methodology and will prepare a document detailing a recommended plan for developing waste repositories in crystalline or argillaceous formations. The study will include a proof-of-concept task and designate priorities for basic research needs in order to reach a national objective of achieving safe, economical, and acceptable radioactive waste storage in the mid 1980's. The study contains three principal elements: an information system, workshops, and a geotechnical assessment study document. Work on all elements has been initiated. Development of

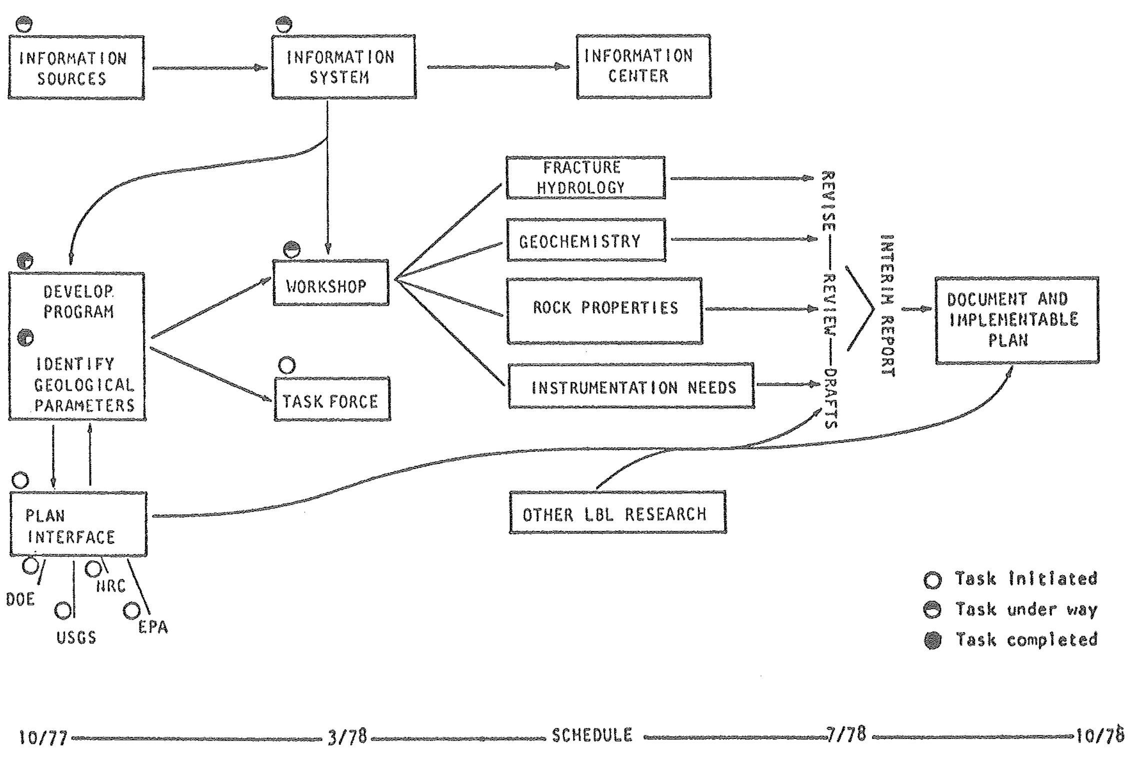

Figure 1. Schematic of geotechnical assessment for radioactive waste storage in crystalline and argillaceous rock.

the study will be carried out during fiscal year 1978, with completion scheduled for the end of fiscal year 1978. The information system will be operative in early fiscal year 1978. A search of the literature and ongoing projects has been conducted and will be periodically updated. The literature search also served the function of identifying current active researchers in waste management.

The physical and chemical properties of rock types were gathered from the literature and are reported in Table 1. Table 2 was compiled to illustrate how these properties might affect waste storage. The preliminary study indicates that all three types have potentially favorable and unfavorable characteristics. One particularly favorable characteristic of crystalline and argillaceous rocks is "mine stability," which indicates a potential for retrieving canisters of waste materials for several decades following emplacement.

The topical workshops will focus upon basic research and instrumentation needs and the state-of-the-art for several phases of the waste management system: siting, design, excavation, construction, and monitoring short-term and long-term operation. The workshops include broad topical areas and are scheduled for Spring 1978. A matrix of rock characteristics (Table 3) has been developed to guide in outlining the questions for the topical sessions. Preliminary workshop formats have been prepared and participant lists begun. Attention will be given to design concepts and instrumentation needs for repositories sited in these rock types. Proof-of-concept criteria will be prepared in early fiscal year 1978. Liaison with the Department of Energy and other agencies is an integral part of the study plan. The plan will prepare a final geotechnical assessment document detailing the study elements and an implementable plan.

The drafting of a plan for assessment of argillaceous and crystalline rock for waste storage will be completed at the end of fiscal year 1978. It will recommend and designate priorities for basic research needs that the Department of Energy

Table 1. Physical and chemical properties of rock types.[a]

	Crystalline Rock			
Physical Properties	Granite	Basalt	Shale	Salt
Average Composition (wt. percent)				
SiO_2	70.0	49.0	58.1	(Salt is 97-99% NaCl) (Ref. 2, p. 277)
TiO_2	.4	1.4	.7	
Al_2O	14.5	15.7	15.4	-
Fe_2O_3	1.6	5.4	4.0	-
FeO	1.8	6.4	2.0	-
MnO	.1	.3	Trace	-
MgO	.9	6.2	2.4	-
CaO	2.0	9.0	3.1	-
Na_2O	3.5	3.1	1.3	-
K_2O	4.1	1.5	3.2	-
volatiles P_2O_5	.2	.5	.2	-
volatiles H_2O	.8	1.6	5.0	.01 to .67 (Ref. 2, p. 277)
volatiles CO_2	-	-	2.6	not available
volatiles SO_2	-	-	.6	not available
Dominant type of crystal structure (Ref. 7)	framework silicate	framework silicate	sheet silicate	ionic bonding
Specific gravity (average)	2.61-2.65	2.04-3.01	2.4-2.94	2.16 (Ref. 3)
Grain size (mm)	0.1-12.0	0.12.0	<0.01	10-40
Moh's hardness	5.83-6.5	3.95-6.21	3.16-5.68	2.5 (Ref. 3)
Solubility	low	low	low	high
Compressive strength (psi)	8,250-35,400	2,470-52,000	4,970-34,800	1,080-5,000
Modulus of Elasticity (10^6 psi)	3.85-6.41	0.91-13.9	6.73-9.87	0.35-0.5 (Ref. 2)
Characteristic Fracture patterns (Ref. 5)	Several sets, off vertical	Vertical columnar fractures	not available (bedding plane?)	not available
Types of principal permeability	fractures	fractures, interstitial	fractures	-
Interstitial porosity (percent)	0.5-3.0	0.9-3.7	0.7-45 (Ref. 4)	<1
Interstitial permeability (gpd/ft^2)	9×10^{-7} - 5×10^{-6}	4×10^{-5} - .9	7×10^{-7} - 4	1.3×10^{-4} - .07
Cation exchange capacity (milliequivalents/100g)	-	.5-2.8	10.0-41.0	-
Melting point (°C)	~700	~1050	not available	800 (Ref. 4)
Thermal conductivity (w/m°C)	2.60-3.77	1.47-1.72	1.2-2.9	5.35-7.22
Average linear thermal expansion coefficient ($\Delta L/L\Delta T$, °C, over 20° - 100° range)	$8\pm3\times10^{-6}$	$5.4\pm1\times10^{-6}$	not available	40×10^{-6} (Ref. 2, p.266)
Thermal Diffusivity (cm^2/sec) (Ref. 5)	0.10-0.14	.006-.007	not available	.02 (Ref. 6)

[a] Unless attributed to another source, data are from Ekren et al., Table 17.[1]

Table 2. Implications of some rock properties for deep burial of radioactive wastes by rock type.

Characteristic	Impact	Crystalline	Argillaceous	Salt
Thermal Conductivity	Allowable power density of waste	high to low	low	high
		0	–	+
Permeability	Radioactive nuclide transport velocity	High to very low, through fractures	High to very low, through fractures	very low
		0	0	+
Solubility	Long-term stability	low	low	high
		+	+	–
Strength	Mine stability	high	low	low
		+	–	–
Plasticity	Mine stability	low	high	high
		+	–	–
	"Self-sealing" quality	–	+	+
Ion-exchange	Ability to absorb radio-nuclides	usually none	high	none
		–	+	–
Density	Long-term gravitational stability when deeply buried	usually high	low to high	low
		+	0	–
Volatile content	Shattering on heating, radiolytic gas formation	low	high	low to high
		+	–	0
Generalized geologic environment of large continuous bodies		In continental shields, mountain ranges, volc. plateaus	In sedimentary basins	In sedimentary basins
	Unfavorable association with gas, oil, water-bearing beds	+	–	–
	Proximity to seismic zones	0	+	+
Generalized distribution in U.S. of large continuous bodies	Availability in arid zones & zones of low population density	West, North, East	East, Central West	Central, East
		+	0	–

+ = favorable to waste storage
– = unfavorable to waste storage
0 = not clearly favorable or unfavorable (because of intermediate value or wide range of values)

should consider funding. In addition to the plan document, there will be available a comprehensive literature collection and computerized information system on radioactive waste storage in crystalline and argillaceous rocks.

In Situ Field Studies of Seepage in "Dry" Mines

The study objective was directed towards finding a site in the United States for development of field techniques to study hydraulic properties of deep fractured rock bodies. An existing mine or mines, giving access to several levels at least 1000 ft deep, was assessed as being required. Accordingly, inquiries were made in Utah, Nevada and New Mexico to find such a site. The commitment of effort has, however, been minimized by constraint of time.

Two visits to Reno were made by Dr. D.T. Snow to confer with Nevada University and Bureau of Mines geologists, and to confer with several mine managers. Nine mines have tentatively been rejected in favor of two that are adjacent to intrusive stocks, much as in Stripa, Sweden. Anaconda's Victoria Mine near Ely follows a dry breccia pipe to 500 ft in limestone near an intrusive. The shaft has been pump-tested and the mine is in the process of abandonment. General Electric Co.'s Nevada-Massachusetts Mine is in tactite, up to 1800 ft deep. The active mine is 1000 ft deep, making 45-50 gpm. Holes drilled into granite below are wet. The Shoal Event site at Fallon is hydrologically unsuited to project needs because numerous faults cut the shaft, producing increasing permeability with depth.

Dr. T. Doe made inquiries in Utah, yielding one possibility, Hecla's Mayflower Mine, in granite. Others are in sedimentary rocks: the Park City mines were wet but are now drained; the Tintic mines include the hot, wet Bergen Mine and the drained Trixie Mine.

Dr. D.T. Snow visited the New Mexico Bureau of Mines at Socorro to inquire of staff geologists and

Table 3. Topical matrix for the geotechnical assessment of raw storage in crystalline or argillaceous rock.

I. GEOLOGY	V. FRACTURE SYSTEMS
1. Structure	1. Width fracture zones
2. Petrology	2. Fracture spacing
3. Stratigraphy	3. Fracture continuity
4. Chronology	4. Degree of interconnection
5. Resources	5. Aperture distribution
6. Thermal gradients	6. Fracture strength (normal and shear)
7. Geomorphology	7. Fracture potential
	8. Stress-flow characteristics
II. HYDROLOGY	9. Fracture failure modes
1. Surface	
2. Subsurface	VI. ROCK PROPERTIES [f(T,P,t)]
3. Paleohydrology	1. Porosity (fracture and matrix)
4. Potential field	2. Permeability (single and multiphase)
5. Velocity field	3. Thermal
6. Unsaturated flow	4. Mechanical
7. Recharge mechanism	5. Radiation effects
	6. Gouge properties
III. SEISMOLOGY	
1. Regional seismicity	VII. GEOCHEMISTRY
2. Fault activity	1. Water chemistry
3. Microseismicity	2. Isotopic composition
4. Geodectics	3. Water sources and ages
5. Potential fault development	4. Rock chemistry
6. Induced perturbations	5. Rock-fluid interaction
	6. Adsorption-desorption
IV. TECTONISM	7. Secondary alteration
1. In situ stress field	8. Chemical diffusion
2. Regional fabric	

to telephone some mine managers. Some 13 known mines were discounted, along with six potash mines, in favor of one possibility worth further inquiry: the Federal Resources, Inc. Bonnie "85" Mine near Lordsburg is the deepest in New Mexico, 2250 ft through basalt into granodiorite. It is flooded to 1500 ft and closed down, but the company would be interested in reopening the mine for research.

Plans for further work in fiscal year 1978 include similar brief surveys in Texas, Washington, South Caroline, Tennessee, and Canada. During calendar 1978 a list of one or two mines per state will be submitted to DOE for approval and clearance through the respective state channels. Thereupon, individual field plans are to be developed to disclose in detail a) variations of hydrology with depth, b) comparative fracturization, c) stress indications with depth, d) geological controls on water testing, and e) logistical problems and advantages of each site.

Laboratory Investigations on Ultralarge Rock Samples

The objective of this task is to investigate flow through fractures in ultralarge rock samples up to 2 m in diameter to help determine the appropriate sample size that should be collected in the field.

A key technical problem in determining the acceptability of a repository site in argillaceous or crystalline rocks is to be able to assess the magnitude of water movement through fractures in the rock mass. The traditional approach to this problem has been to investigate flow through rock samples whose diameter did not exceed 15 cm. However, there is increasing evidence that a size effect must be taken into account. For example, recent experimental studies on samples of fractured rock ranging from 15 cm to 100 cm in diameter have clealy shown that the decrease in fracture flow rates with increasing normal stress in the small samples was not conservative.

We have undertaken a laboratory investigation of this problem using a very large testing machine that can handle rock samples up to 2 m in diameter and 2.5 m in length. A comparison of results on various sample sizes from LBL, LLL and USGS should indicate an optimum laboratory scale for future testing and whether a scaling factor can be introduced to relate laboratory results to specific site situations.

In fiscal year 1977, the principal activity was the selection of a rock type for the scale effect study and the design and procurement of a closed-loop control mechanism to be installed on the existing large testing machine in order to achieve the level of accuracy and reliability that is required by this project.

The new control systems, when installed, will allow closed-loop control of load, stroke, confining pressure, water pressures and flowrate. In addition, it will have the capability of nonsteady-state determination of rock and fracture permeability.

The anticipated installation dates are April 1978 for the load system and September 1978 for the pressure and permeability system.

Mathematical Modeling Objective

The goals of this task are to modify and/or develop appropriate numerical models that can simulate the coupled effects of: 1) heat and fluid flow through rock masses containing deformable fractures and 2) thermo-mechanical stress distributions in such rock systems.

A brief survey accomplished in 1977 reveals that no current analytical or numerical method can adequately simulate the coupled effects of stress, heat and fluid flow. Existing computer codes that address one or more aspects of the problem fall into the following categories:

1) Three-dimensional Finite Difference (FD) or Integrated Finite Difference (IFD) codes for nonlinear heat transfer modeling (for example, TRUMP,[8] and HEATING 5[9]).

2) Three-dimensional FD or IFD codes for fluid flow in deformable porous media (TRUST[10]).

3) Three-dimensional IFD codes for nonlinear heat conduction, convective heat and mass flow in isotropic porous media containing one set of fractures deformable in response to normal stress (CCC[11]).

4) Two-dimensional Finite Element (FE) codes for nonlinear heat conduction in anisotropic media subject to convective and radiation boundary conditions (DOT-DETECT[12]). A three-dimensional code is available commercially but not in the open literature.

5) Three-dimensional FE codes for linear and nonlinear uncoupled thermal and mechanical stress analysis of anisotropic media (for example, SAP[13] and NONSAP[14]).

6) Two-dimensional FE codes for coupled effects of stress and transient fluid flow in anisotropic porous or impermeable media containing deformable fractures.[15,16]

7) Three-dimensional FE codes for transient heat and fluid flow in porous media.

Codes of the types (1), (2), (3), and (6) are available at LBL. Codes of types (4) and (5) have been developed at University of California, Berkeley Campus.[13,14]

Although numerical methods are more versatile, analytical solutions, wherever applicable, can provide detailed information for three-dimensional configuration at a fraction of the cost and time required to set up numerical models. Accordingly, efficient computer programs have been developed 1) to model heat conduction in isotropic media for an arbitrary three-dimensional assembly of finite line or cylindrical heat sources using the Green's function method and numerical integration, and 2) to analyze transient packer well-test for in situ determination of fracture properties in an impermeable rock matrix using the Laplace transform.[17]

Predictions from these analytical solutions have been confirmed by limited numerical modeling using codes of types (2) and (3). A number of case studies have been carried out using these analytic solutions and reports are being written on the details.

Additionally, large-core fully dynamic storage versions of codes of types (4) and (5) have been implemented at the LBL CDC 7600 computer. One of these (SAP) has been interfaced with the heat conduction program. A number of case studies of thermal stress have been performed. For instance, preliminary results indicate that although the temperature fields of two 5-kW cylindrical heat sources do not interfere after two years, the resulting thermoclastic fields do interact owing to the pervasiveness of thermally induced displacement.

During fiscal 1978, efforts will be directed toward the following:

1) Further improvement of the programs based on analytical solutions, such as including an arbitrary time-dependent source function.

2) Interfacing the analytical heat conduction solution and/or heat transfer codes of types (1), (3) or (4) to the nonlinear FE code NONSAP.

3) Further thermal stress case studies.

4) Documentation of the coupled stress-flow code, type (6), and case study.

5) Development of coupled stress-fluid flow/heat flow programs using smeared out "overlay" models in the far-field and discrete fracture models in the near-field.

6) Study of steam formation effects.

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INSTRUMENTATION NEEDS TO ASSESS, EVALUATE AND MONITOR RADIOACTIVE WASTE STORAGE IN DEEP BURIAL SITES

T. Simkin and M. O'Brien

INTRODUCTION

The Earth Sciences Division in cooperation with the Engineering and Technical Services Division is undertaking a project, funded by a seed grant from the LBL Director's Office, to conduct a symposium to document instrumentation for all phases of waste repository development and to synthesize those findings and recommendations into an LBL report.

The symposium, to be scheduled in spring of 1978, will have national and international participation with experts representing scientific research, instrumentation, industry and nuclear waste. Based on the symposium results, LBL may propose to become the lead laboratory for instrumentation studies related to terminal storage of radioactive wastes in geologic structures.

ACCOMPLISHMENTS DURING 1977

The Instrumentation Needs Symposium follows the conference on "Fluid Flow in Largely Impermeable Rocks," chaired by LBL in Texas, and the cooperative study on waste storage at Stripa, Sweden. From the conference and the Swedish study it is clear that instrumentation needs have not been defined, and much of the present technology is antiquated or untested for emplacement at great depths, pressures and temperatures. The symposium will make a preliminary start in identifying thermo-mechanical and hydrologic instrumentation needs. These needs are greatly compounded when consideration of monitoring 30,000 canisters is added.

PLANNED ACTIVITIES FOR 1978

As part of the preparations for the symposium, LBL will start to define the critical information and target needs for waste monitoring and related instrumentation during several phases: baseline, construction, emplacement, short-term (up to 100 years) and long-term monitoring. Both surface and subsurface monitoring will be considered. Figure 1 provides the starting point for planning and conducting this symposium.

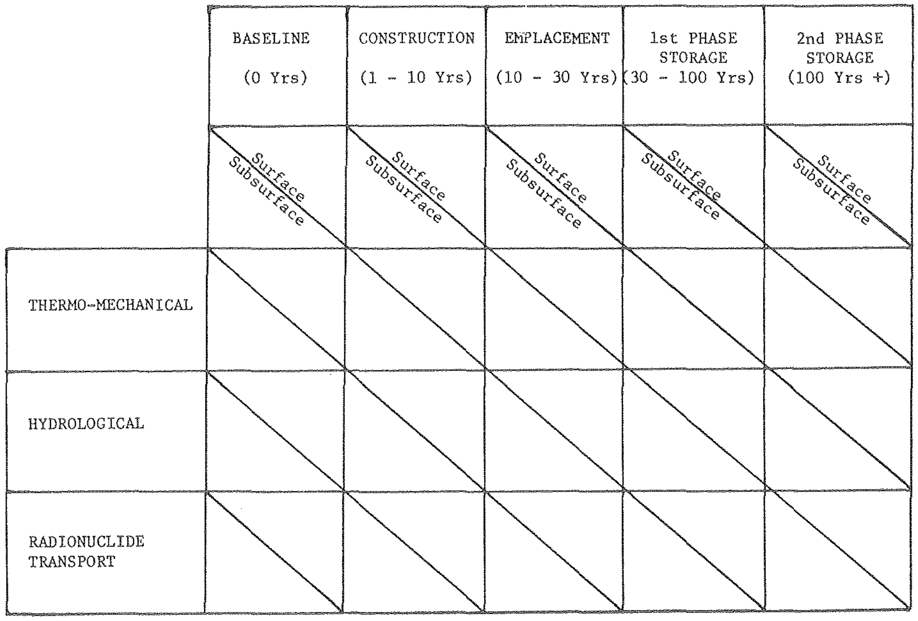

Figure 1. Radioactive waste storage monitoring matrix. The matrix represents the starting point of the workshop to define what physical properties require monitoring and the assessment of current instrumentation technology to measure those characteristics. The purpose is to define research requirements.

WASTE ISOLATION SAFETY ASSESSMENT PROGRAM

J. A. Apps

INTRODUCTION

The progress and results obtained during fiscal year 1977 for LBL Contract No. 45901AK are reported in LBL-7022, Theoretical and Experimental Evaluation of Waste Transport in Selected Rocks.[1] This project is part of the Waste Isolation Safety Assessment Program (WISAP), which is managed for the DOE Office of Waste Isolation by Battelle Pacific Northwest Laboratories. In particular, this project supports task 5 of WISAP, the collection and generation of transport data. Within task 5 is subtask 4, which addresses the problem of understanding the mechanisms of radionuclide transport and the impact of such mechanisms on radionuclide distribution coefficients. The goal of this project is to establish a basis on which radionuclide distribution coefficients can be reliably predicted for geological environments of the type anticipated for terminal radioactive waste storage facilities.

DISTRIBUTION COEFFICIENT DETERMINATION

It is well known that the distribution coefficient (K_d), defined thus:

$$K_d = \frac{\text{mole of radionuclide sorbed/g}}{\text{moles of radionuclide in solution/ml}}$$

is a semiempirical parameter, subject to variation as a result of the chemical and physical conditions under which it is measured. These conditions vary greatly, depending on whether the environment is adjacent to a terminal storage facility or is similar to the environment normally encountered in a laboratory experiment. Laboratory measurements of K_d vary significantly from experiment to experiment. Therefore, the applicability of currently available measurements to the prediction of radionuclide behavior in rocks is questionable. Table 1 gives a tentative list of factors that might influence a typical K_d determination and the errors that might result from omitting these factors when extrapolating data from laboratory to subsurface conditions expected in a host rock adjacent to a terminal storage repository. It is obviously important to identify the critical factors influencing the magnitude of empirical distribution coefficients for given radionuclides, and to establish the variation in those factors under differing host rock conditions.

PROJECT SUMMARY

The radionuclides chosen for this study include thorium, uranium, plutonium, neptunium, americium, curium, iodine, and technetium. During fiscal year 1977, emphasis has been placed on the actinides plutonium, neptunium, americium, and curium. The host rock types being considered include acid igneous rocks (granite, rhyolite), basic igneous rocks (gabbro, dolerite and basalt), sedimentary rocks (argillites, sandstone, and limestone), and metamorphic rocks (if deemed appropriate). Although the study is generic and

TABLE 1. Factors influencing K_d for a given radionuclide, based on a comparison between conditions in a typical soil column adsorption study and conditions expected in a terminal storage repository.

Parameters	Principal effect	Soil column test	Subsurface terminal storage facility	Potential effect on K_d
1. Solution chemistry				
a. Major components	Ionic strength Activity coefficients Complexing	Very variable. Composition determined by condition the test is designed to simulate.	Determined by host rock chemistry and by other factors including the leaching chemistry of the waste product.	Unpredictable — probably 10^{-3} to 10^{+3}.
b. Minor components	Complexing	Same as above.	Same as above.	Same as above.
c. pH	Complexing Chemical potential	2-11, depending on the nature of the test	5 - 8. Buffering of heterogenous and homogeneous equilibria keep the pH range within narrow limits.	10^{-5} to 10^{+5}
d. Eh	Chemical potential	Variable, usually oxidizing, and dependent upon pH.	Variable, over a narrower range, usually reducing.	Up to 10^{10} or even more
2. Radionuclide concentration and speciation	Supersaturation Polymerization Metastable equilibrium	10^{-6} to 10^{-9} mole/kg. As ionic, polymeric, and particulate forms.	Uncertain, but probably very low, depending on leaching characteristics of waste product form (glass) possibly 10^{-9} to 10^{-12} mole/kg. Principally as ionic species.	Difficult to estimate, but could be very large for amphoteric species near the isoelectric point ($\sim 10^6$).
3. Flow rate	Metastable equilibrium Transport Mechanisms Changes in apparent surface area contacted	$\sim 10^{-3}$ to 10^{-1} cm/sec	10^{-3} to 10^{-7} cm/sec	Sufficient flow rates could lead to different rate controlling transport mechanisms (e.g. ionic or molecular diffusion) also lead to different thermodynamic controls (0 to 10^6)
4. Permeability	Flow rate (see above)	10^{-2} to 10 Darcys	10^{-3} to 10^{-8} Darcys	Same as above.
5. Duration	Radionuclide decay Daughter formation Front reinforcement	$\sim 10^5$ sec	Up to 10^{13} sec	None considered at this time.
6. Surface area	Adsorption	Up to 10^5 cm^2/g; Dispersed clays, humus, fine particulates, loess, etc.	$\sim 10^2$ cm^2/g Fractures, microfractures, intergranular pores	$\sim 10^3$
7. Path length	Dispersion	10^2 cm	2×10^7 cm	No anticipated effect on K_d.
8. Temperature	Complexing Solubility Adsorption	25°C	10 to 100°C	Up to 10^3

does not pertain to a specific site, greater emphasis is being placed on rocks from the Nevada Test Site and the Hanford Reservation near Richland, Washington.

The project includes both theoretical and experimental investigations organized into several interrelated subtasks, as illustrated in Figure 1. These subtasks all support an attempt to define the

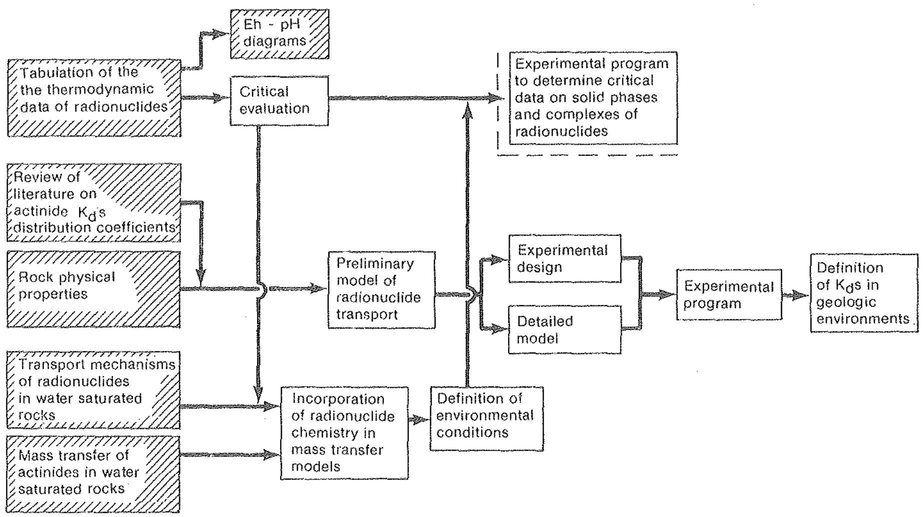

Figure 1. Logic chart for LBL Waste Isolation Safety Assessment Program-5: Theoretical and Experimental Evaluation of Waste Transport in Selected Rocks. (Hatching indicates the task is complete.)

environmental conditions expected in the water-saturated host rocks of a terminal storage facility and to determine the transport mechanisms of radionuclides in these rocks. This information can then be used to relate the thermodynamic and transport properties of radionuclides to the corresponding distribution coefficients, which then can be used with confidence in a computer simulation of radionuclide transport. Without such an effort, there is a danger that experimentally obtained distribution coefficients will be misinterpreted when calculations are made to determine transport through rock to the biosphere.

During fiscal year 1977, the following subtasks were performed.

1. Thermodynamic data were tabulated for those aqueous complexes and solid phases of plutonium, neptunium, americium, and curium likely to form in the natural environment.
2. Eh-pH diagrams were computed and drafted for plutonium, neptunium, americium and curium at 25°C and one atmosphere.
3. The literature on distribution coefficients for plutonium, neptunium, americium, and curium was reviewed.
4. Preliminary considerations were determined for an experimental method of measuring radionuclide transport in water-saturated rocks.
5. The transport mechanisms of radionuclides in water-saturated rocks were reviewed.
6. A computer simulation was attempted of mass transfer involving actinides in water-saturated rocks.

Progress in these tasks is reported in LBL-7022.[1] Subtasks 1, 2, 3 and 4 are complete. The progress made in subtask 5 is represented by an initial theoretical survey to define the conditions needed to characterize the transport of radionuclides in rocks. This task will be refined and will continue in fiscal year 1978. Subtask 6 has begun but is not complete. Progress in this task will be reported more fully in 1978.

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MODELING OF UNDERGROUND HEATER EXPERIMENTS SIMULATING HIGH-LEVEL RADIOACTIVE WASTE REPOSITORIES IN HARD ROCK

T. Chan, N. G. W. Cook, and C. F. Tsang*

INTRODUCTION

In the assessment and design of underground high-level radioactive waste repositories in hard rock it is essential to understand the thermo-mechanical response of the rock mass to decay heat and the consequent effects on fluid flow through fractures. Furthermore, many of the physical and chemical processes controlling the rate of release of the radionuclei to the biosphere are thermally activated. The United States-Sweden Cooperative Program is a major effort toward achieving a better understanding of such complex phenomena.

An important part of the cooperative program is a set of heater experiments in an abandoned mine at Stripa. The project reported here was started in May 1977 to provide theoretical support for design and data interpretation of these experiments. The objectives are:

(1) To apply and modify existing analytical and numerical methods to model heat and/or fluid flow, thermally induced stress, and coupled fluid flow and stress.

(2) To develop numerical models for coupled heat-fluid flow-stress analysis.

At every stage of the project the theoretical work has been, and will be, closely related to the field experiments. Thus far the temperature calculations have strongly influenced both the design of the heaters and the experimental layout. The predicted temperature, displacement, and stress fields will be stored in an on-site computer to be used for real-time comparison with field data by means of a computerized data collection and graphic display system so that on-the-spot decisions on modifications to the experiments, if necessary, can be made. Conversely, all raw data will be captured and transferred back to LBL. These will be used for extracting in situ rock mass properties by comparison with theoretical models and, in conjunction with laboratory testing results, for guiding the modification and improvement of models. Such an iterative approach is necessary in view of the variability and complexity of geological systems.

1977 ACCOMPLISHMENTS: THERMAL CALCULATIONS[1]

During 1977 efforts were devoted primarily to temperature, thermal deformation, and stress calculations since these are the major quantities to be measured in the field experiments. The three heater experiments modeled included a 3.6-kW full-scale heater (2.59-m long, 0.32-m diameter), a 5-kW full-scale central heater (same size) surrounded by eight 1-kW peripheral heaters (4.27 m in length) arranged in a ring of 0.9-m radius, and a planar array of eight time-scaled heaters (0.81-m long, 0.1-m diameter) with 3-m or 7-m spacing. The linear scale factor is 1:3.2, giving a corresponding time scale factor of $1:3.2^2 = 1:10.2$. A brief account of the work accomplished follows.

Development

It was recognized that, in view of the short thermal diffusion time across the radius of the heater, the temperatures in the rock can be obtained quite accurately by approximating the cylindrical heater by a finite line. Accordingly a solution to the heat conduction equation for a finite line source has been derived using Green's function method. This solution involves only a single integral, as compared to the double integral expression necessary for a finite cylinder,[2] and therefore takes far less computational time to evaluate by numerical integration. A computer program, FILINE, based on this line source solution, has been developed to calculate the temperature field due to various arrays of finite line sources. The image technique was used to model isothermal or adiabatic boundary conditions at the floor of the heater drift. Numerical comparison with Mufti's[2] finite cylinder solution (which we coded into a program CYNDER), and with an integrated finite difference model (using program CCC[2]), has confirmed the validity of the finite line source approximation.

The main advantage of the analytic method is that if the temperature needs to be known only at a few isolated points in space and time, as often happens in the design phase, the analytic solution has to be evaluated just at those particular points, whereas in more general numerical schemes such as finite difference or finite element methods, the temperature must be computed over the entire domain of model space and time. Thus, the amount of effort required in model set-up and in computation to aid and/or assess design changes or alternatives differ by orders of magnitude. A further consideration, specific to the present application, is that two of the experiments consist of 3-dimensional heater arrays so that a temperature file for approximately 10^6 points in space and time for each experiment is necessary for graphic display of the spatial temperature distribution and time history. Computational economy, therefore, becomes an important issue.

Cases Studied

Table 1 summarizes the various cases modeled. Sample results are illustrated in Figures 1-3.

Some important results and conclusions are:

(1) After a few weeks of operation the ring of peripheral heaters will give rise to a nominally uniform temperature distribution within its circumference, thus providing a reasonable simulation of the background temperature rise due to other waste canisters in a repository, Figure 1. The temperature within the ring increases by about 100°C in 30 days and 140°C to 180°C (depending on boundary conditions) in 2 years.

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Table 1. Cases of thermal calculations completed in 1977.

Cases	Source Function: Constant power	Decaying power	None (i.e. infinite medium)	Boundary Condition(s): Isothermal	Adiabatic	Newton's law of cooling	Model
Test case							
One 1-kW	●		●				FILINE
full-scale	●		●				CYNDER
heater	●			●	●	●	CCC
Field situations							
One 3.6-kW full-scale heater	●		●	●	●		FILINE
One 5-kW full-scale heater	●			●	●	●	CCC
One 5-kW full-scale central heater + eight 1-kW peripheral heaters	●		●	●	●		FILINE
Eight time-scaled	●	●	●	●	●		FILINE
heaters	●			●	●		CCC
One time-scaled heater in cased borehole	●			●	●		CCC

(2) If the 5-kW central heater and the eight 1-kW peripheral heaters were to be operated concurrently throughout a two-year period, temperature increase within a radius of 1 m would be higher than 300°C (over 450°C near the main heater hole), Figure 2, exceeding the temperature ratings of the instruments. Accordingly, it has been decided to switch on the peripheral heaters only after the central heater has been operating for about one year.

(3) In the time-scaled experiment, appreciable interaction occurs between the two heaters spaced 3 m apart (corresponding to 9.6 m for full-scale), but not between the two with 7 m spacing (corresponding to 22.4 m for full-scale) within a period of 30 days (corresponding to 307 days for full-scale), Figure 3a. After 2 years (20.4 years for full-scale), Figure 3b, all the heaters will be interacting; temperatures will still be increasing everywhere but only gradually, and the temperature distribution will still be far from uniform. It is therefore important to carry out detailed canister arrangement studies for repository designs to ensure retrievability. In other words, gross thermal loading should not be used as the sole thermal criterion.

(4) Installation of a stainless steel casing in each time-scaled heater hole will have only minor effects on the temperature distribution.

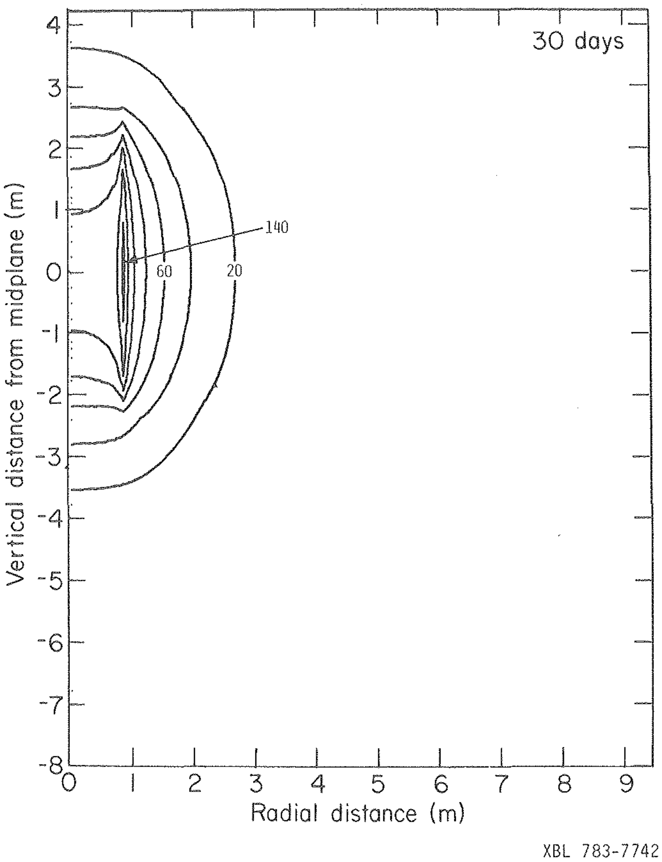


Figure 1. Isotherms of temperature rise (°C) due to eight 1-kW peripheral heaters after a period of 30 days. The drift floor is modeled as the isothermal boundary; the longitudinal plane section is illustrated.

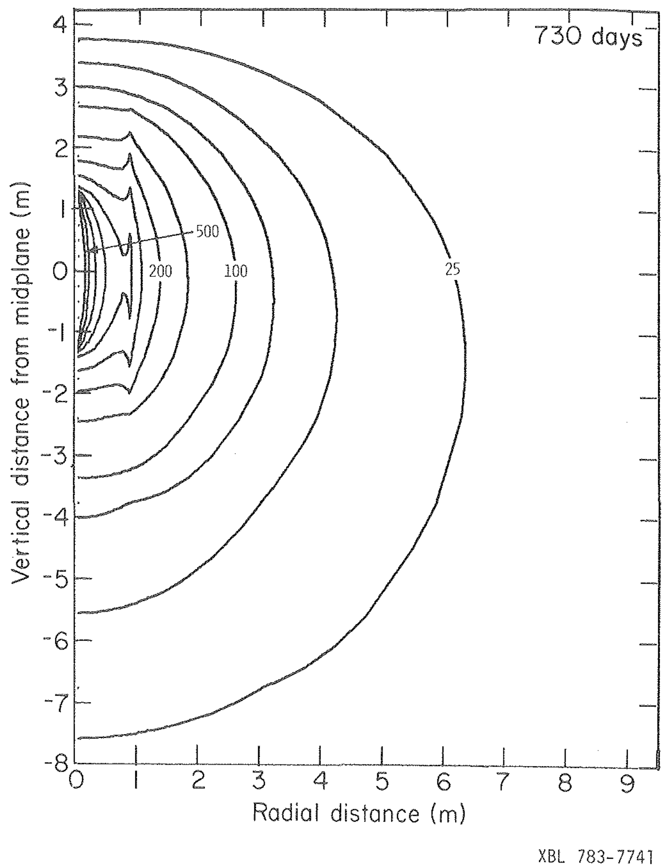
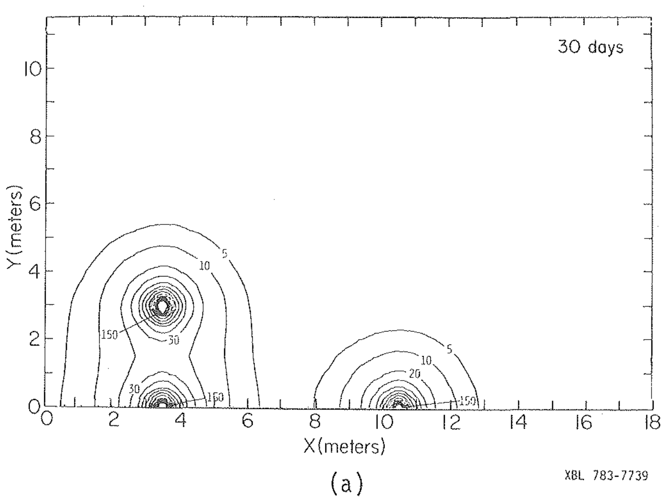


Figure 2. Isotherms of temperature rise (°C) due to a 5-kW full-scale central heater and eight 1-kW peripheral heaters after 2 years of concurrent operation at constant power. The drift floor is modeled as the isothermal boundary; the longitudinal plane section is illustrated.



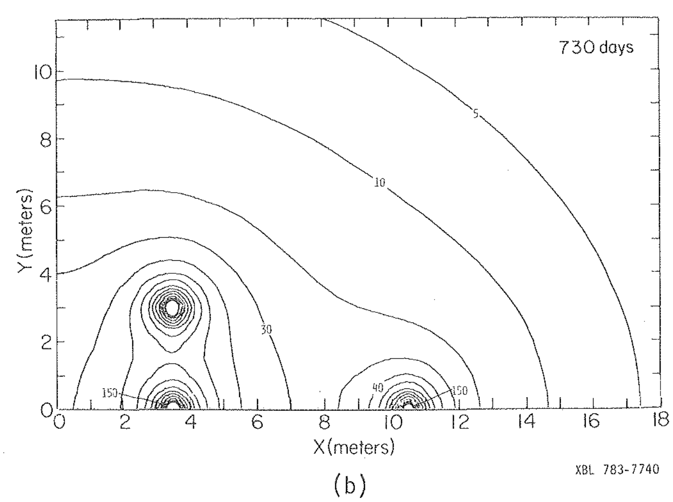


Figure 3a. Isotherms of temperature rise (°C) due to an array of eight 1.1-kW time-scaled heaters after a period of 30 days, with decaying power simulating high-level reprocessed light water reactor waste. This is an infinite medium model; one quadrant of the horizontal section through the heater mid-plane is illustrated.

Figure 3b. Isotherms of temperature rise (°C) due to an array of eight 1.1-kW time-scaled heaters after a period of 2 years, with decaying power simulating high-level reprocessed light water reactor waste. This is an infinite medium model; one quadrant of the horizontal section through the heater mid-plane is illustrated.

Thermal Stress Calculations[4]

Our heat conduction program FILINE has been interfaced to the finite element code SAPIV.[5] Thermal stress analyses have been carried out for the three aforementioned heater experiments using various loading and boundary conditions. Only a cursory discussion will be given here.

For the full-scale experiment with peripheral heaters operating simultaneously, Figures 4 and 5 depict the tangential and axial components of the thermal stress as a function of radial distance along the heater mid-plane. Both axial and tangential stress will exceed the unconfined compressive strength of intact Stripa granite[6] within a period of 90 days. Thermally induced displacements are also very substantial. Maximum displacement will be over 2 mm in 90 days and over 3 mm in 2 years. This is a result of the high temperatures as well as high thermal gradients (see Figure 2). Consequently, thermal decrepitation is to be expected.

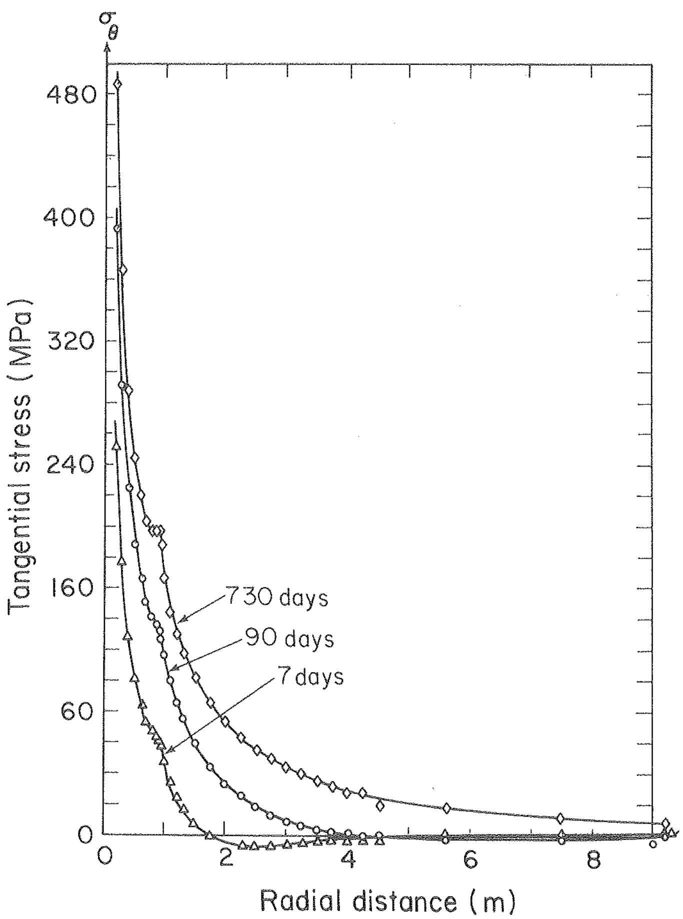


Figure 4. Thermally induced tangential stress (MPa) as a function of radial distance (m) along the heater mid-plane for the full-scale experiment consisting of one 5-kW constant-power central heater and eight 1-kW peripheral heaters after various periods of concurrent operation.

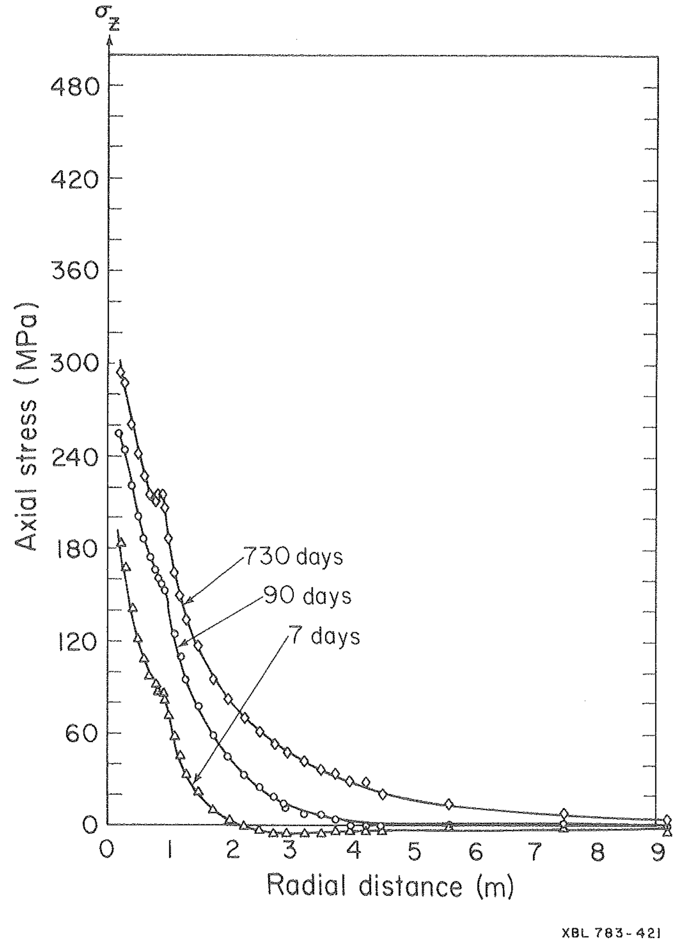


Figure 5. Thermally induced axial stress (MPa) versus radial distance (m) along the heater mid-plane for the full-scale experiment consisting of one 5-kW constant-power central heater and eight 1-kW peripheral heaters after various periods of concurrent operation.

Even without the peripheral heaters, compressive stresses around the heater hole would still be higher than the unconfined compressive strength. Accordingly, decrepitation detection devices will be installed in the boreholes.

Tensile stresses (see Figures 4 and 5) comparable to the unconfined tensile strength and the in situ stress will also be induced. Hence, the possibility of fractures opening with consequent reduction in thermal conductivity and positive thermal feedback cannot be excluded.

Another observation is that the displacements for the two heater experiments both persist over a long distance, implying that the two experiments are not entirely independent.

PLANNED ACTIVITIES FOR 1978

1. Calculate the temperature field for the full-scale heater experiment with peripheral heaters switched on after the central heater has been operating for one year.

2. Attempt to extract in situ material properties of rock mass by comparison of theoretical prediction with field data by means of type-curve fitting or least-squares fit.

3. Superpose the stress and displacement solutions for the two full-scale heater experiments to obtain their combined effects.

4. Include effects of water in fractures and temperature-dependent thermal conductivity using the CCC program.[3]

5. Model effects of canister placement on stress and thermal fracturing close to drifts by using existing nonlinear finite element programs.

6. Incorporate thermal stress (uncoupled) effect into a finite-element program for coupled stress-transient heat flow recently developed at the University of California, Berkeley[7] and apply it to case studies using the temperatures calculated in 4 above, as input.

7. Start work to investigate effects of steam production and pressure buildup.

8. Start work (in cooperation with Prof. R.L. Taylor of University of California, Berkeley) to develop techniques for coupled heat-fluid flow-stress analysis.

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TRANSIENT FLOW IN TIGHT FRACTURES

J. S. Y. Wang, T. N. Narasimhan, C. F. Tsang, and P. A. Witherspoon

INTRODUCTION

Hydrogeology is an important consideration in selecting a deep continental geologic formation as a site for radioactive waste storage. The potential spread of radionuclides from the storage site to the earth surface will be mainly through groundwater transfer. Fractures are the main conduits of water in most hard rock formations. Thus, to estimate the possible rate of waste spread, it is important to have reliable measurements of the aperture size and connectivity of the underground fracture network. At depths of 1-2 km, the fractures are likely to be very tight, with apertures in the micron range which are difficult to measure with the usual downhole tools. In this paper, a pulse packer test for in situ study of tight fractures is presented.

In a packer test (Figure 1), a pressure pulse is applied to water sealed between two packers and the pressure decay at the wellbore is monitored. When the well intersects fractures, the pressure decline is due to the flow into the fractures. Since water is viscous, the smaller the fracture aperture, the larger the resistance to flow or the

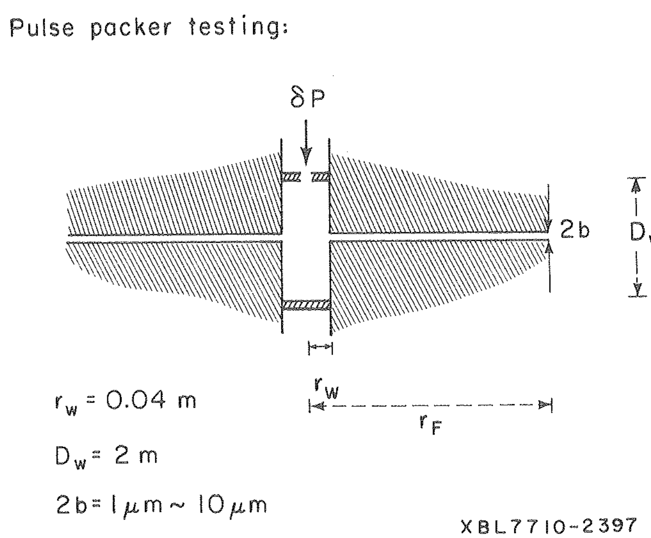

Figure 1. Schematic of a wellbore intersecting a fracture.

slower the pressure decline. By measuring the pressure change as a function of time the fracture properties can be analyzed. At early times the pressure change depends mainly on the near-wellbore fracture resistance. By analyzing the "short-time" data the fracture aperture can be estimated. At later times, the fracture geometry will affect the pressure change. Thus the "long-time" data contains further information about the continuity and connectivity of the fracture system.

The objectives of the project are:

1. Perform analytic and numerical modeling of the transient fracture flow in response to a pressure pulse at the wellbore.
2. Study the dependence and scaling of the pressure change on the wellbore and fracture dimensions and fluid properties.
3. Develop simple procedures for quick estimation of the fracture apertures.
4. Study the effect of fracture multiplicity, orientation, and connectivity.
5. Generalize the data to multi-packer-well interference tests.

This project started in June 1977. The present report is based partially on a talk[1] presented at the Invitational Well Testing Symposium at Berkeley in October 1977.

ACCOMPLISHMENTS FOR 1977

Transient pressure changes were calculated for several geometrical arrangements of single and multiple fractures intersecting the wellbore. Analytic and numerical methods were used to solve the diffusivity equation which governs the fracture flow of slightly compressible water. Analytic solutions were derived with the Laplace transformation procedure. Numerical modeling was accomplished using computer program "TRUST" developed at Lawrence Berkeley Laboratory.

In Figure 2 the pressure declines at the wellbore for single infinite and finite fractures with 10-μm and 1-μm apertures are plotted. For a finite fracture, the external boundary can either be closed, Figure 2(a), or maintained at the ambient pressure, Figure 2(b). For a 10-μm fracture in either Figure 2(a) or 2(b), the pressure change occurs within several minutes. For a 1-μm fracture, it takes almost an hour before an appreciable pressure change is noted and several days to complete the pressure decline. By one order of change of the fracture aperture, the decay time changes by approximately three orders of magnitude. This dependence originates from the cubic dependence of the fracture flow conductance on the aperture. Over a short time the finite fracture boundary effect has no influence on the pressures and all curves of a given aperture tend to coincide. A simple procedure for quick estimation of the aperture can be developed. For different apertures, the time required for the pressure declining to a given value differs. In Figure 3, the aperture 2b is plotted against the time required for the pressure to reach 0.95, 0.90, or 0.85 of the initial value. The uncertainties

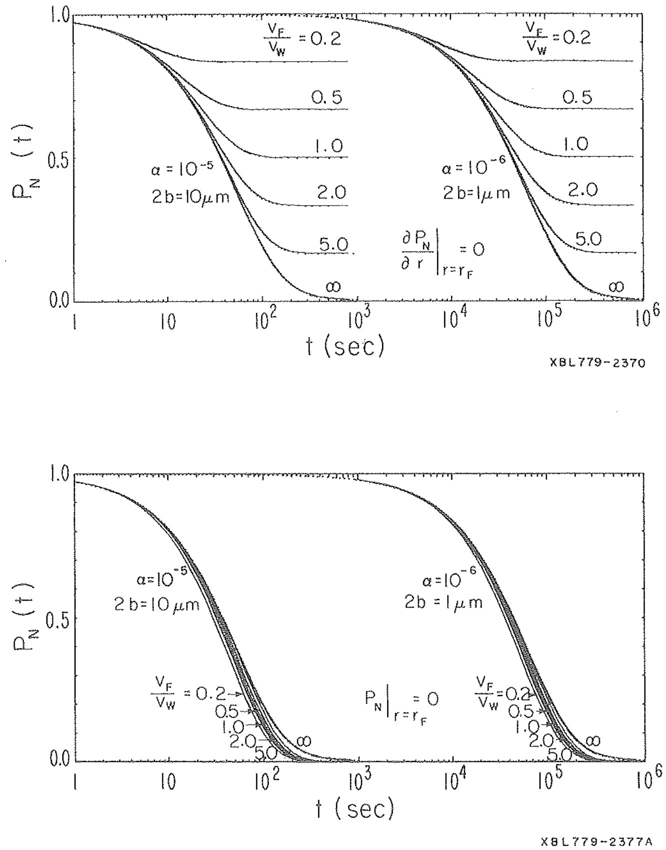

Figure 2. Normalized pressure decay at a wellbore intersected by a single fracture of aperture 2b and fracture-wellbore volume ratio V_F/V_W. The fracture boundaries at radius r_F are either closed [zero pressure gradient in (a)] or open [zero pressure in (b)]. α is the dimensionless leaking capacity. Solid lines = analytic solutions. Dots = numerical results.

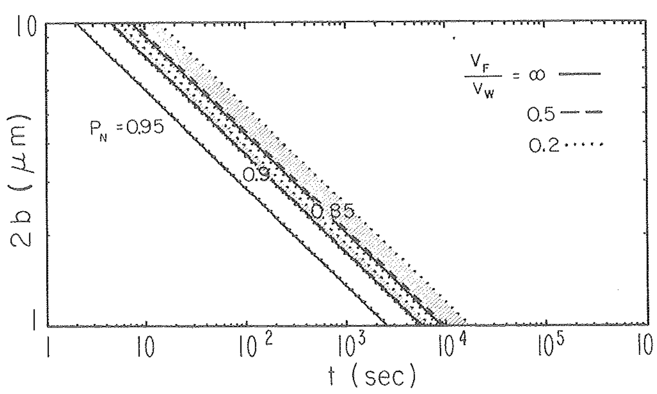

Figure 3. The relation of the aperture 2b and the time required for the pressure to decay to a given fraction P_N of the initial applied pressure. The uncertainty due to finite fracture boundary is shown by the shaded bands.