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Geothermal and Geosciences Program

Annual Report 1975

Energy and Environment Division

For Reference

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Lawrence Berkeley Laboratory University of California/Berkeley

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Geothermal and Geosciences Program , Annual report

This report is a reprint of the Geothermal and Geosciences section of the 1975 Annual Report (LBL-5299) of the Energy and Environment Division of Lawrence Berkeley Laboratory. The sources of funding for these various projects are indicated by the abbreviations explained below.

DBER	Division of Biomedical and Environmental Research
DGE	Division of Geothermal Energy
DPR	Division of Physical Research
EG&G	Edgerton, Germeshausen & Grier
LBL	Lawrence Berkeley Laboratory
NSF	National Science Foundation
OPA	Office of Public Affairs

Most of the projects were funded by the Division of Physical Research.

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Geothermal and Geosciences

INTRODUCTION

The Energy and Environment Division's geothermal and geosciences program is concerned with the practical development of this energy source and with basic research in the geosciences to provide fundamental information for the development of more sophisticated energy systems in the future.

Several subjects of interest to geothermal development and the supporting basic science are included in the division program. A main effort is the program for the evaluation of techniques to locate and assess potential liquid-dominated geothermal resource areas. Field activities in north central Nevada have employed a variety of geophysical, geological, and geochemical techniques for diagnostic evaluation.

Scientific and engineering projects include the formulation and improvement of numerical models of geothermal reservoirs, reservoir compaction, reinjection of spent fluid, and two-phase heat and mass transfer in porous media systems. Theoretical work is also being done to formulate equations predicting the thermodynamic properties of the mixed aqueous electrolytes present in geothermal brines. This information has been used in calculations aimed at the optimization of power cycles and will be of use to others in power plant design. The kinetics of silica dissolution and precipitation, directly related to scaling in geothermal power plants and the sealing of geothermal reservoir boundaries, is also being investigated. Physical models are being developed to study geothermal convection and reservoir dynamics, and test facilities are being designed to study the properties of rock-fluid systems related to geothermal use. This latter project will also be significant to the thermal recovery methods applied to the extraction of fossil fuels.

A brief reservoir assessment of the Raft River Geothermal Field in Idaho has been made using flow tests on existing wells. Some exploratory work has been done to correlate natural radioactivity with geothermal mineralization and rock type. Other field equipment has been built and tested.

The long range geosciences program includes geochemical studies of mantle source material, and the high temperature properties of silicate liquids relating to heat flow and other magmatic processes.

A project supporting the entire geothermal community is the National Geothermal Information Resource (GRID), which serves as an information center, critically analyzing and evaluating data, and interfacing the information file with the user.

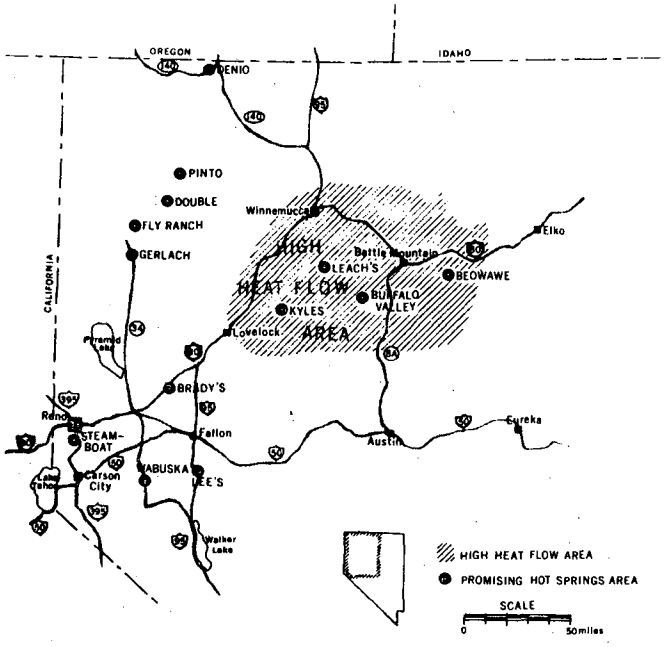
GEOTHERMAL FIELD ACTIVITIES, NORTH-CENTRAL NEVADA

H.A. Wollenberg, T.V. McEvilly, and H.F. Morrison

A program for evaluation of techniques to locate and assess potential geothermal resource areas is underway in north-central Nevada.

Geothermal field activities have included a preliminary electrical resistivity survey, reconnaissance geologic mapping and geochemical sampling of the Beowawe area, and extensive geological, geophysical, and geochemical surveys in Buffalo and Grass Valleys, encompassing Buffalo Valley Hot Springs and Leach Hot Springs, respectively. (See Fig. 1 for locations of these areas.) Surface surveys and heat flow measurements are complete in Buffalo Valley, and surface geophysical surveys are presently underway in Grass and Buena Vista Valleys, near Leach and Kyle Hot Springs. (A more detailed explanation of the program and descriptions of methods may be found in Refs. 1 and 2.)

Parameters that are diagnostic in evaluating and comparing geothermal areas were described in detail in Ref. 1. Temperature at depth within a hot spring system is estimated from silica and alkali-element abundances of the hot water. Conductive heat flow is calculated by combining the downhole thermal gradient with thermal conductivity measured on representative core samples. Electrical resistivity reconnaissance is done by bipole-dipole and telluric surveys, while more detailed resistivity data is obtained by the dipole-dipole method. Generally, hot water zones are associated with low resistivity. Microearthquakes (earthquakes with magnitudes $\ll 1$) are detected by very sensitive seismometers whose signals are radio-telemetered to a central data acquisition station. A microearthquake zone may indicate the presence of geothermal fluids in a fault zone. Electrical self-potential may



Hot Springs in Northwestern Nevada

Fig. 1. Location map of northwestern Nevada, showing prominent thermal spring areas within and outside of the Battle Mountain High heat flow region. (XBL 735-676)

indicate upwelling thermal water as well as normal ground water flow. The nature of spring deposit material is a rough indication of the quality of a potential geothermal resource; generally deposition of silica indicates higher temperatures at depth than do calcium-carbonate deposits.

Important geophysical parameters at Buffalo, Grass, and Buena Vista Valleys are compared in Table 1. The tabulated results of Grass Valley surveys, the combination of electrical resistivity and teleseismic P-delay data suggests the presence of a capped, hot-water reservoir area north-northwest of Leach Hot Springs. Also of interest, two heat flow anomalies were discerned several kilometers southwest and south-southeast of the springs.[3] These are indicated by the 4.9 and 5.1 heat-flow-unit values on the accompanying map (Fig. 2). Neither one is associated with any surface hydrothermal manifestation, however both are significant conductive thermal anomalies. Therefore, it is planned to expand the heat flow coverage of southern Grass Valley, by drilling at least one more ~ 50 meter-deep gradient hole, to furnish data for a contour map of heat flow in the area.

Surface geophysical measurements in Buena Vista Valley indicated the presence of a large self-potential anomaly east of Kyle Hot Springs. The nature of this anomaly, whether it is primarily

Table 1. Comparison of important parameters at Buffalo, Grass, and Buena Vista Valleys.

Parameter	Buffalo Valley	Grass Valley (Leach H.S. Area)	Buena Vista Valley (Kyle H.S. Area)
Temperature at depth as indicated by spring water chemistry	130°C (SiO_2) at B.V. H.S. 150°C (SiO_2) at spring on west playa fault zone	150-170°C (SiO_2 and Na-K-Ca); possibly exceeds 200°C, considering mixing of near-surface cool water	170-190°C (SiO_2 and Na-K-Ca)
Conductive heat flow	4.6 hfu[a] ~ .5 km east of B.V. H.S.; 3 hfu on west playa fault zone	9 hfu ~ 1 km northeast of springs; ~ 5 hfu at 2 locations several km SSE and SW of hot springs	No measurements to date
Electrical resistivity	General broad area of shallow, low resistivity (5-10 ohm-m) over playa area; probably associated with electrically conductive old lake bed and playa sediments. Very small low resistivity zone associated with B.V. H.S.	Discrete zones of low resistivity (1-5 ohm-m) at depth, associated with L.H.S. and an area NNW of springs. Another area of low resistivity corresponding to zone of high heat flow, low gravity and microearthquakes, 6 to 8 km SSE of L.H.S.	Surveys underway
Microearthquakes	Latest surveys confirm absence of activity in Buffalo Valley; some activity in Tobin Range west of the Valley	Zone of activity trending ~ ENE - WSW in the vicinity of Panther Canyon, ~ 6-10 km SE of L.H.S.	No apparent activity during short (~ 2 week) survey
Parameter	**Buffalo Valley**	**Grass Valley (Leach H.S. Area)**	**Buena Vista Valley (Kyle H.S. Area)**
Self potential	Positive anomaly associated with hot springs	Anomalous "structure" near and away from hot springs	Large anomaly in hills east of hot springs; presently being detailed
Spring deposit	Predominantly $CaCO_3$	Predominantly SiO_2	Presently depositing predominantly $CaCO_3$, but evidence of abundant SiO_2 deposition in recent past

a. 1 hfu = 1μcal $cm^{-2}sec^{-1}$

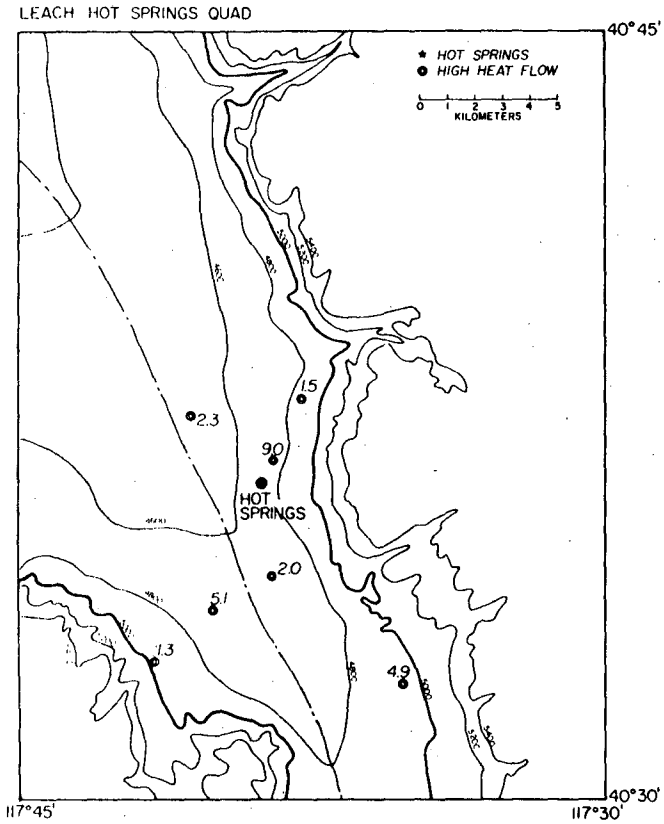


Fig. 2. Topography (elevation in feet) and heat flow (μcal $cm^{-2}sec^{-1}$) in the vicinity of Leach Hot Springs, Nevada.

(CBB 762-1627)

associated with geothermal activity, mineralization, or groundwater flow, will be examined by detailed geophysical, geological and geochemical surveys.

From inspection of Table 1 and the preceding paragraph, it is evident that, from existing data, Grass Valley offers a more promising geothermal resource area than does Buffalo Valley. Based on what we know now, if a geothermal resource does exist in Buffalo Valley, it is probably diffuse and of relatively low temperature, compared to a more well-defined, higher temperature geothermal area in Grass Valley.

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MIXED EXPLICIT-IMPLICIT ITERATIVE FINITE ELEMENT SCHEME FOR THE DIFFUSION EQUATION*

T.N. Narasimhan and P.A. Witherspoon

INTRODUCTION

Geothermal reservoirs form complex physicochemical systems and their mathematical simulation is very much dependent on approximate numerical schemes. Hence, a significant part of the reservoir modeling efforts of the Geothermal Group is directed towards formulating and improving appropriate numerical models. In recent times, the finite element method (FEM) has evolved to become a powerful integral formulation for numerical analysis of the diffusion equation. It provides significant advantage, especially in handling complex geometry and general tensorial quantities such as anisotropy, stress, and dispersion. At the same time, the traditional finite difference approach, although inconvenient for handling complex geometry or general tensors, possesses inherent advantages of mathematical simplicity and closeness to the physical approach. A.L. Edwards[1] of the Lawrence Livermore Laboratory incorporated an integrated form of the finite difference method (IFDM)[2] into a powerful computer program called TRUMP for solving the heat transfer equation. This program employs a very efficient explicit-implicit approach combined with an iterative algorithm, thereby avoiding the need for inverting large, sparse matrices. Since it should be of great advantage to combine the special advantages of FEM (handling tensors) with those of the IFDM (mixed explicit-implicit approach, iterative solution), we examined the theoretical bases of the FEM and the IFDM and have successfully developed a mixed explicit-implicit, iterative FEM algorithm. This algorithm has been incorporated into a computer program called FLUMP (mnemonic for Finite eLement and trUMP). This new program is suitable for solving the diffusion equation under complex geometry and with material properties, sources and boundary conditions varying with the dependent variable or with time.

An illustrative example of the saturated-

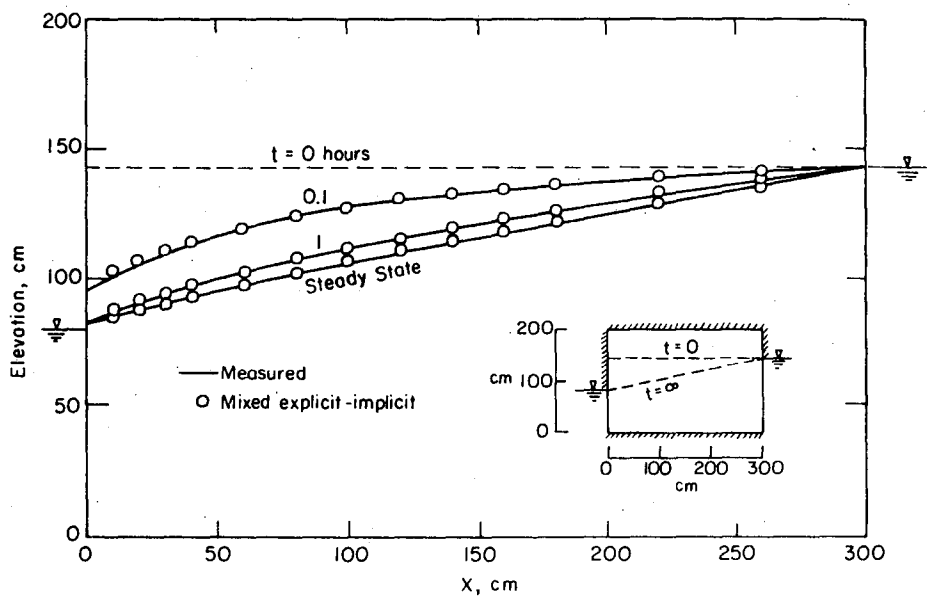

Fig. 1. Saturated-unsaturated flow problem; initial and boundary conditions and the evolution of water table.
(XBL 765-1912)

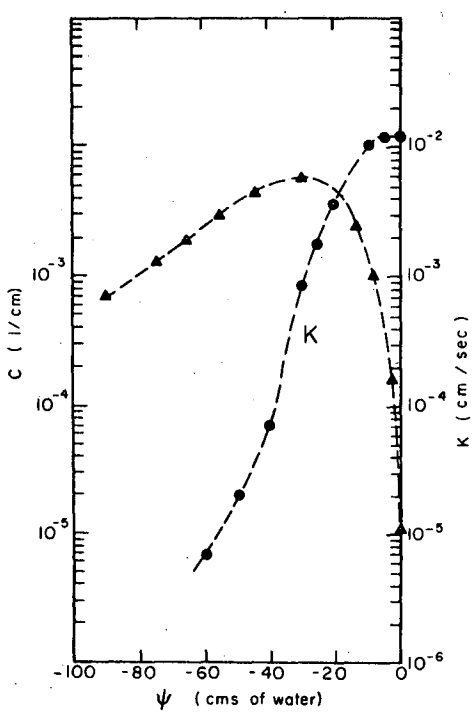

Fig. 2. Saturated-unsaturated flow problem; variation of material properties.
(XBL 764-2826)

unsaturated seepage of water in a sand box will show the effectiveness of this mixed explicit-implicit approach. For a detailed account of the theory the reader is referred to Refs. 3 and 4.

ILLUSTRATIVE EXAMPLE

This example is the nonlinear problem of saturated-unsaturated flow of water in a rectangular flow region. In addition to the role of gravity in governing the flow of water, the problem is complicated by the fact that both k and c are strong functions of the pressure head $\psi = \emptyset - z$, where z is the elevation.

The problem pertains to a careful experimental investigation conducted by Vauclin et al.[5] and is governed by the equation

$$\nabla \cdot k(\psi)\ \nabla\ [z+\psi] = c(\psi)\ \frac{\partial\psi}{\partial t}\ .$$

The initial and boundary conditions of the problem are presented in Fig. 1.

The nonlinear functional dependence of k and c on ψ are shown in Fig. 2. Also in Fig. 1 are shown the positions of the surface $\psi = 0$ (the "water table") calculated at different instants of time compared with the experimentally observed positions. We see that the agreement is good. The cumulative amount of water depleted from storage within the flow region calculated for various instants of time is compared with the experimental observations in Fig. 3. Considering the complexities of controlling a saturated-unsaturated flow experiment, the discrepancies noted in Fig. 3 should be considered acceptable.

PLANNED ACTIVITIES

Further developmental work of the mixed explicit-implicit scheme is expected to follow two general directions. The first of these would be to incorporate the transport of heat or chemical species into the governing equation along with the introduction of thermal or chemical dispersion. Dispersion is known to be of tensorial nature, and the dispersion tensor generally rotates with time in response to changes in the velocity field. The FEM offers the most powerful way of handling general tensors. It is extremely difficult to handle the tensors in a general way with finite

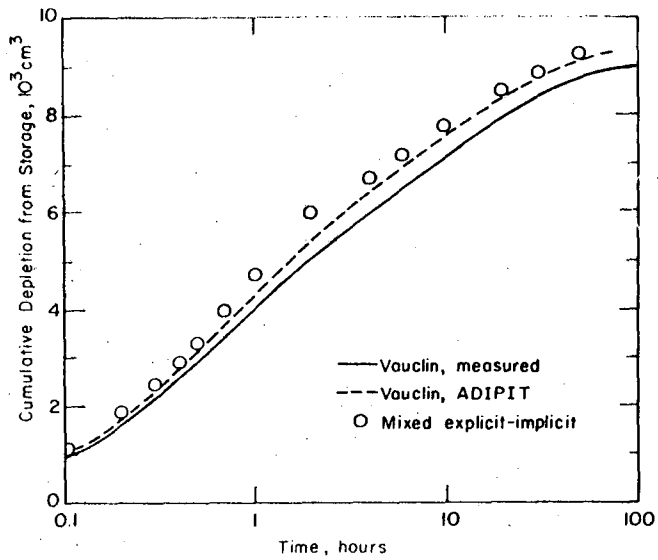

Fig. 3. Saturated-unsaturated flow problem; cumulative depletion from storage as a function of time. (XBL 765-1910)

difference techniques. The second line of work would be to extend the FLUMP program to general three dimensions. Basically this extension would require an examination of the conductance matrix that would result from using three-dimensional brick elements and a study of their relation to diagonal dominance.

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* Condensed in part from LBL-4405 and -4406.

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REINJECTION IN GEOTHERMAL RESERVOIRS*

C. F. Tsang and P. A. Witherspoon

INTRODUCTION

Reinjection of used geothermal liquids into the producing reservoir has been proposed by many investigators as an effective way to avoid or alleviate the following problems normally associated with geothermal energy production:

(1) Disposal of used geothermal waters with minimum environmental impact.
(2) Land subsidence due to the reduced pressure in the reservoir upon fluid withdrawal.
(3) Depletion of fluid and heat from the reservoir.

However, reinjection creates a zone of relatively cold water around each injection well that grows with time and eventually will reach the production wells. After breakthrough occurs, the temperature of the produced water drops and drastically reduces the efficiency of the whole operation. It is thus important to design the system of production and injection wells in order to prevent injected water breakthrough before a specified time, and to maintain the temperature variations at the production wells after breakthrough within reasonable limits.

This project was started during 1975 and we have set ourselves the goal of calculating quantitatively the temperature decrease due to reinjection for a given system of production and injection wells. Based on this, the physical basis for the optimization of fluid and heat recovery from geothermal reservoirs will be investigated, using as parameters the distribution of production and injection wells and their flow rates. This study, when coupled with a knowledge of above-ground utilization facilities, will afford a development of resource management strategies to optimize the economics of geothermal energy extraction.

ANNUAL ACTIVITIES

The project of calculating the temperature change in a system of production and injection wells was successfully completed. The calculation is based on a simple two-dimensional steady state model[1] developed by A.C. Gringarten and J.P. Sauty of the Bureau de Recherches Geologiques et Minieres at Orleans, France. To illustrate the results, we display in Fig. 1 the simple case of a doublet of one production well and one injection well. The dotted lines represent the stream lines and the solid lines, the thermal fronts. In this particular case (with parameters given in the figure caption), the temperature at the production well stays at the reservoir temperature for 5.7 years, at which time the cold injected water reaches the production well by the shortest stream line. After this time, temperature begins to drop asymptotically to the injection temperature. One point to note is that the cold thermal front from the injection well advances toward the production well much more

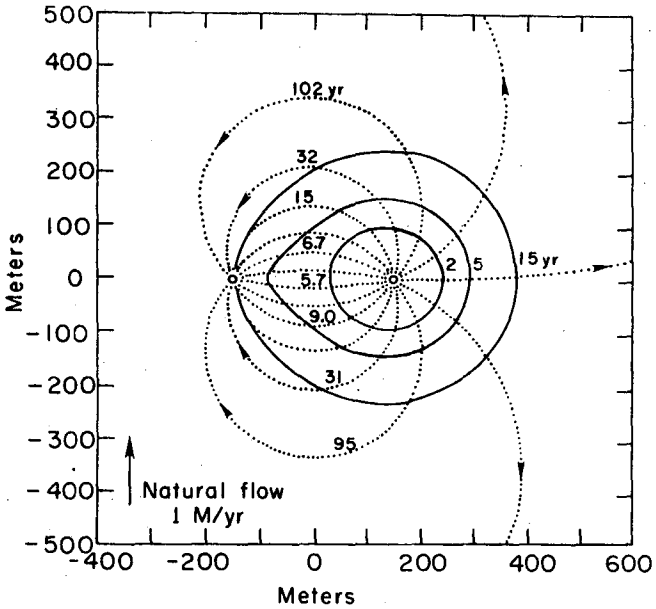

Fig. 1. A production-injection doublet. The dotted lines are streamlines and the solid lines are the thermal fronts. Numbers are given in years. The separation between the wells is 300 meters. A regional flow of 1 meter/year is assumed in the positive-Y direction. Heat capacity of the rock is assumed to be 0.5 cal/cm^3/°C and its thermal conductivity 0.006 cal/cm/sec/°C. Thickness of the aquifer is 100 meters with a permeability of 10%. Flow rate of either well is 100 cubic meters/hour. Temperature of the reservoir is 70°C and the temperature of water reinjected is 40°C. (XBL 7510-8598)

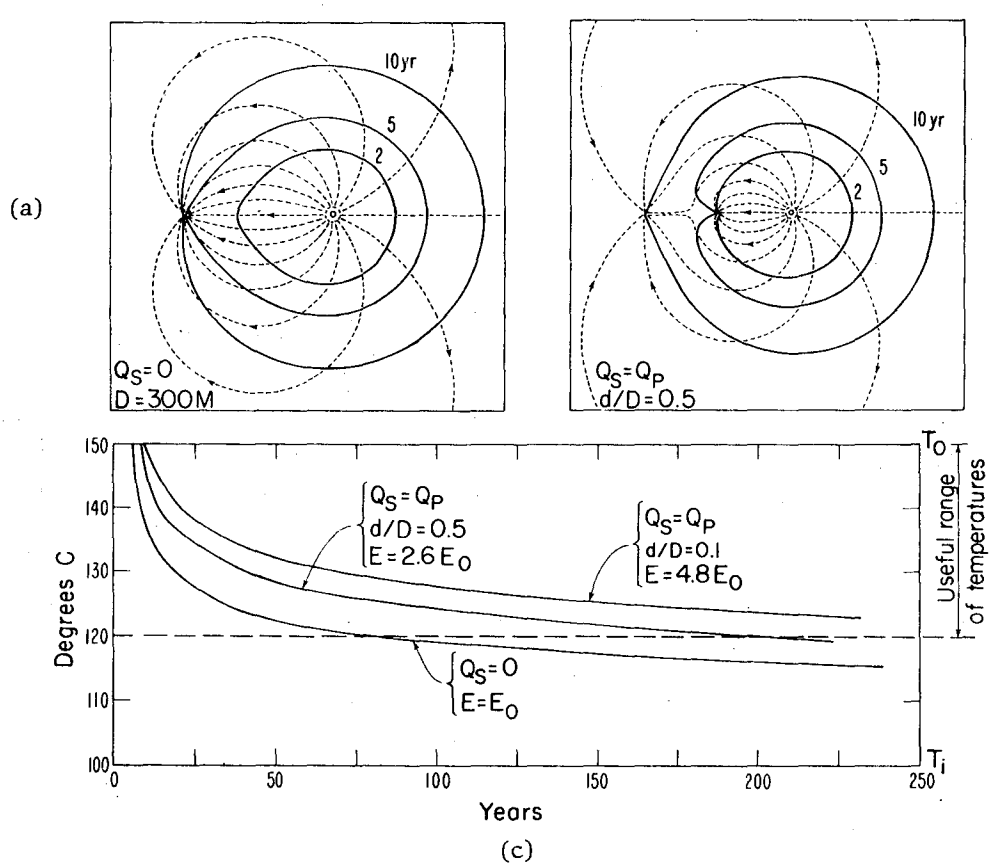

Fig. 2. The top half of the figure indicates the streamlines (dashed lines) and the thermal fronts (solid lines) of the doublet system with and without screening. The lower half shows the temperature at the production well as a function of time in three cases, (a) no screening well, (b) screening well half-way between production and injection wells at a flow rate equal to production, and (c) same as (b) but with screening well at 1/10 the separation distance from the production well. The symbols D and d represent the distances from the production well to the injection well and to the screening well, respectively. (XBL 768-3878)

slowly than the hydrodynamic front due to the heating of the injected water by the porous medium. The program developed is able to handle complicated systems of many production and injection wells.

In connection with the reinjection problem, we have developed a new concept (called the Screening Concept) of protecting the producing well from reinjection effects by means of one or more screening wells appropriately positioned in between. The basic idea is that by producing water from the screening wells, one can intercept the cold water and put it back into the injection wells so that if the flow rate at the production well is Q_p, and that at the screening well is Q_S, the flow rate at the injection well will be $-(Q_p + Q_S)$. The physics of the idea have been worked out, and it is found that the time it takes for the cold, reinjected water to break through at the production well may be increased by as much as a factor of two. After breakthrough, the rate of temperature drop at the production well will be reduced,but not as drastically as when no screening wells are used.

Figure 2 illustrates a simple example of a doublet with and without the screening well. It can be seen from the top half of the figure that the effect of the screening well is to intercept the stream lines, thus pulling the thermal fronts toward it. The lower half of the figure illustrates the temperature curves. The energy extracted is proportional to the flow rate times the area under these curves above a certain given temperature below which the water will not be useful. To make a comparison we take a case of a doublet without screening in which the production and reinjection rates are each Q, to be compared with a case with screening in which the production and screening wells are each at a flow rate Q and the injection at 2Q. It is found that the accumulative extracted energy of the system with the screening well (for the case where it is 1/10 the doublet separation distance from the producing well) after 50, 100 and ∞ years are respectively 1.6, 2.0 and 4.8 times larger than that for the unscreened system.

We have also made calculations on the same model for a system of many production and reinjection wells with screening wells in between. A gain in the energy extracted is also obtained, but the amount depends on the distribution of wells in each given case.

PLANNED ACTIVITIES

An economic feasibility study will be made on the reinjection problem as well as on the new screening concept.

Further physical basis of various means of optimizing fluid and heat recovery in a system of production and reinjection wells will be studied.

FOOTNOTE AND REFERENCE

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NUMERICAL SIMULATION OF RESERVOIR COMPACTION IN LIQUID DOMINATED GEOTHERMAL SYSTEMS

M. J. Lippmann

INTRODUCTION

Geothermal systems are receiving increasing attention as an alternative source of energy. A large number of these systems are of the hot water reservoir type, which are dominated by circulating liquid that transfers most of the heat and largely controls subsurface pressures. During the exploitation of such geothermal systems (i.e., withdrawal of hot fluids) a reduction of pressures is inevitable, which, in some areas, may lead to land subsidence. For example, this phenomenon has been observed[1] at the Wairakei Field, New Zealand, where over a ten year period ground subsidence reached up to 4.5 meters.

In addition to vertical ground movements, horizontal displacements are also observed. These effects may rupture the casings of the geothermal wells, reduce and/or reverse the slope of drainage and irrigation canals, and affect surface installations (e.g., buildings, roads, steam lines, etc.). One method of reducing ground movements is to reinject[2] the used geothermal liquids into the reservoir to minimize pressure reductions.

The objective of this project, started in September 1975, is to develop computer programs to calculate the ground subsidence in liquid dominated geothermal systems. These codes will permit the prediction of how much and where subsidence might be expected in an area where geothermal fluids are produced. Also, by knowing the geologic characteristics of the geothermal system, the location of new production and reinjection wells can be optimized to minimize the environmental effects (subsidence) caused by geothermal energy development.

ANNUAL ACTIVITIES

A computer program was developed to simulate the effects of production as well as reinjection on the deformation of geothermal reservoirs. The program combines the numerical method of Sorey[3] for mass and energy transport with another method by Narasimhan[4] for one-dimensional (vertical) con-

solidation. The model is multidimensional and solves for reservoir deformation in liquid-dominated, heterogeneous, isotropic, non-isothermal systems. Deformation parameters may be non-linear and non-elastic, while the thermal and hydraulic properties can be temperature and/or pressure dependent.

An integrated finite difference technique is used to solve the flow and energy equations, which are interlaced in time. Pore-pressures and temperatures are obtained, and the pressure changes are used to determine the volumetric and vertical deformations.

PLANNED ACTIVITIES FOR NEXT YEAR

1. The new program will be checked against available analytical and experimental results.
2. Attempts will be made to apply the program to real geothermal systems where reliable data are available.
3. The program will be combined with available finite element computer codes in order to calculate surface horizontal displacements.
4. New features will be added to the program (e.g., mesh generation and plotting routines).

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DEVELOPMENT OF A MULTIDIMENSIONAL MODEL FOR TWO-PHASE HEAT AND MASS TRANSFER IN POROUS MEDIA

G. E. Assens

INTRODUCTION

One-phase geothermal systems can be simulated on a computer by use of programs such as SCHAFF.[1] However, in many instances, both liquid water and water vapor are present in a geothermal reservoir; one must even expect that a pure liquid system will eventually evolve into a two-phase system as production goes on.

The drastic changes in the fluid properties as well as the transfer of energy involved at flashing or condensation make the simulation of a two-phase system considerably more difficult than that of a pure liquid or pure vapor system.

The development of a computer program able to handle two-phase flow of heat and mass in one to three dimensions was started in 1973 by Thomas J. Lasseter;[2] it incorporates many of the features of the program TRUMP.[3] During calendar year 1974, the program was applied to some test problems that revealed the necessity of additional development.

ANNUAL ACTIVITIES

Calendar year 1975 was planned to be devoted to a thorough checkup of the program SHAFT. A glossary of terms used in its programming was established. Several errors were corrected, and that part of the program that reads in properties of the fluid and of the porous matrix and transforms them into a table was remodeled.

PLANNED ACTIVITIES FOR 1976

1. Implementation of dynamic storage.
2. Provision for anisotropic media.
3. Insertion of the explicit-implicit mixed mode.
4. Simulation of the behavior of liquid/vapor dominated systems.

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THERMODYNAMICS OF GEOTHERMAL BRINES

Leonard F. Silvester and Kenneth S. Pitzer

The objective is a set of equations predicting the various thermodynamic properties of mixed aqueous electrolytes with particular attention to the temperatures, pressures, and components present in geothermal brines. The properties considered include Gibbs energy, enthalpy, heat capacity, and density, and will provide the basis for both solubility calculations and various heat transfer or heat balance calculations. The results are to be summarized in a form for convenient engineering use in geothermal plant design. This work was initiated through a program under the Materials and Molecular Research Division (LBL) program.

In 1975 the equations developed previously were fitted to osmotic and activity coefficient data, enthalpy data, and heat capacity data on aqueous sodium chloride solutions from various sources. The thirteen parameter equation reproduces the osmotic coefficient data to ± 0.005 over the composition range 0-6M and temperature range 0-300°C, enthalpy data to ± 5-10 cal/mole for compositions of 0-5M at temperatures from 25-100°C, and heat capacity data to ± 0.5 cal/°K for compositions of 0-2M at temperatures from 25-200°C. Details of the data treatment and results in the form of tabulated values of the total Gibbs energy, enthalpy, and heat capacity, plus partial molal and excess thermodynamic quantities of sodium chloride solutions for compositions of 0.6M at 25°C intervals from 0-300°C along with the same quantities in graphical form for compositions of 0-6M at temperatures of 100-350°C are given in Ref. 1.

Current activities planned in 1976 include: 1) extension of the methods used in treating NaCl solutions to the available thermal data on Na_2SO_4, and $MgCl_2$ solutions, 2) analysis of volumetric NaCl solution data, and 3) design and initial construction of a micro-flow high-temperature, high-pressure calorimeter-densimeter.

In the future the methods used in treating NaCl solutions will be extended to other salts of geochemical interest. First, calculations will be carried out for pure solutions of each relevant component. Later the available data for mixtures will be considered. The micro-flow calorimeter-densimeter will be used to obtain needed thermal and volumetric data first on pure solutions and later for mixtures.

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THE USE OF PROGRAM GEOTHM TO DESIGN AND OPTIMIZE GEOTHERMAL POWER CYCLES

M. A. Green and H. S. Pines

PROPERTIES OF CONCENTRATED SALINE BRINES

Some geothermal fields in the Imperial Valley of California are characterized by extremely high concentrations of dissolved salts. These geothermal waters, which can be found at temperatures as high as 360°C, have dissolved solid concentrations as high as 350,000 parts per million. The predominant constituent of these brines is sodium chloride; substantial quantities of magnesium chloride are also found. Experimental thermodynamic data on concentrated brines is lacking. A couple of crude brine models exist but they are not accurate enough. The chemistry of brine solutions is complicated even for the simplest of brine; NaCl in water. Since NaCl is a major component of geothermal brines, our model is based on ionic NaCl solution. The model, which has good theoretical backing, was developed by Silvester and Pitzer.

The model, which has many terms, shows good agreement with measured data. It was designed for use up to 300°C at concentrations up to 6 molar (259,621 ppm) and was extended for use to about 330,000 ppm (8.43 molar) and for lower concentrations it can be used up to 360°C. The model was changed to include the saturated pressure and saturated liquid specific volume. Increased concentrations of NaCl result in an increased boiling point temperature at a given pressure. The vapor that is in equilibrium with the brine (when the concentration is greater than zero) is superheated vapor. The temperature and pressure are the same as the liquid phase. The enthalpy, H, entropy, S, and specific volume, V, of the gas are found using the Keenan and Keyes equation of state. Table 1 is a short T, P, V, H, S, table for brine with concentrations of 0, 100,000 and 200,000 ppm of NaCl. Figure 1 is a plot of H_{liquid} and H_{vapor} versus temperature at various concentrations. From Table 1 and Fig. 1 one can see that the enthalpy (and internal space energy) is less for brine than for pure water. This plays an important role in determining the performance of a geothermal power plant which runs on

Table 1. A short table of saturated liquid pressure, enthalpy, entropy, and specific volume as a function of temperature and concentration for sodium chloride-water brines.[a]

Concentration (ppm)	T (°C)	P (bar)[b]	H (Jg^{-1})	S ($Jg^{-1}°K^{-1}$)	V ($cm^3\ g^{-1}$)
0	50	0.123	104.4	0.336	1.012
0	100	1.013	314.2	0.939	1.044
0	150	4.758	527.3	1.474	1.090
0	250	39.73	980.5	2.425	1.251
0	300	85.81	1239.1	2.886	1.404
100,000	50	0.115	92.2	0.336	0.944
100,000	100	0.946	280.2	0.877	0.968
100,000	150	4.448	469.8	1.353	1.002
100,000	200	14.53	661.8	1.779	1.047
100,000	250	37.14	862.8	2.177	1.105
100,000	300	80.12	1106.4	2.610	1.183
200,000	50	0.110	85.8	0.335	0.910
200,000	100	0.902	264.9	0.850	0.930
200,000	150	4.249	444.6	1.301	0.958
200,000	200	13.90	625.3	1.702	0.993
200,000	250	35.59	815.4	2.079	1.033
200,000	300	77.01	1065.3	2.522	1.076

[a]Vapor values are superheated steam. See the pure water steam tables at the P and T of the liquid phase.

[b]1 bar = $10^5 N\ m^{-2}$.

Imperial Valley brines.

To illustrate the use of concentrated saline brines in program GEOTHM,[2] a simple bi-fluid cycle is used (as an example, see Fig. 2). The brine enters the heat exchanger at 280°C and 90 bar. Air enters an air cooled condenser at 25°C. The secondary working fluid is isobutane. The turbine inlet temperature is 220°C at a pressure of 50 bar. The pump inlet temperature is 36°C at a pressure of 5.2 bar. The pinchpoint temperature difference is 10°C in the brine heat exchanger and 5°C in the air cooled condenser. The efficiencies of the turbine, pump and fan are 80%, 75%, and 50% respectively. Generator and motor efficiencies are assumed to be 98%. The net power from the plant is set at 10 MW.

Two kinds of brine to isobutane heat exchangers are illustrated. The first is a simple tube shell heat exchanger. This kind of heat exchanger is subject to fouling—it is doubtful if the average U factor would ever be over 567 $W\ m^{-2}\ °K^{-1}$ (100 $Btu\ hr^{-1}\ ft^{-2}\ °F^{-1}$). The second type of heat exchanger is a four stage flashing cascade heat exchanger.[3] In each stage the brine is flashed; the vapor is scrubbed by the returning condensate (the vapor is de-superheated in the process): then the vapor is condensed on tubes that carry the isobutane. The condensate returns to the brine; the brine leaves the stage at the same concentration it entered the stage. The brine temperature is determined by the stage pressure; the condensing temperature at the tube surface is the condensing temperature of pure water at the stage pressure. Whenever the concentration is greater than zero, the condensing temperature on the tube is lower than the brine temperature. This has the effect of increasing the pinchpoint temperature difference without decreasing the tube surface area. The potential advantage of the cascade heat exchanger is reduced fouling and increased U factor. The

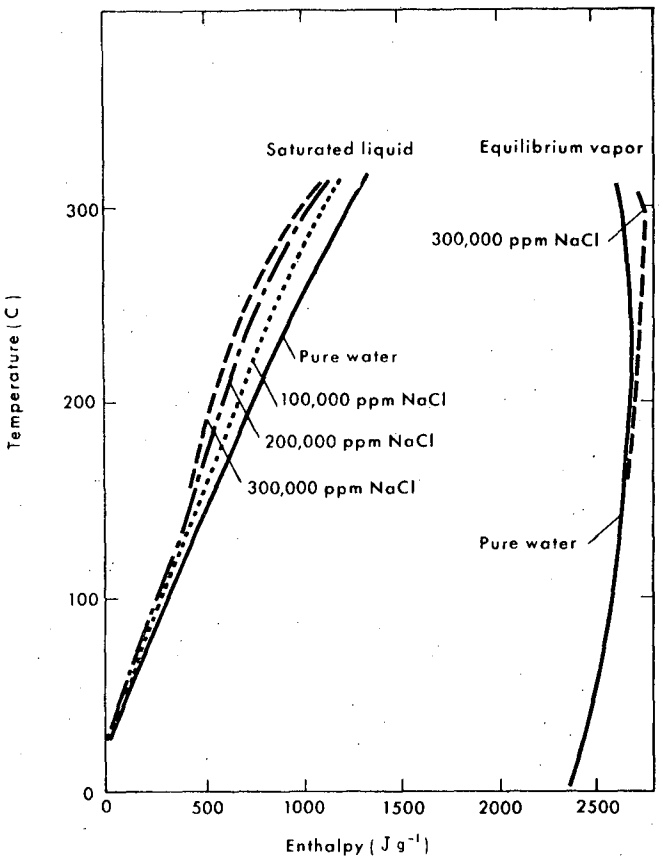

Fig. 1. The enthalpy of a saline brine and steam that is in equilibrium with the brine as a function of temperature and concentration. (XBL 762-2243)

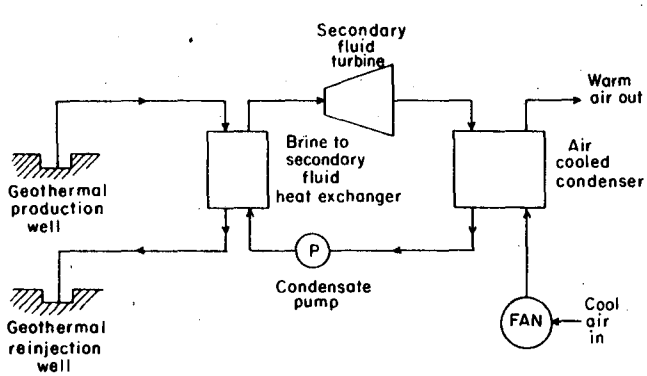

Fig. 2. A simple bi-fluid geothermal power plant cycle with an air cooled condenser. The brine to secondary heat exchanger may be either a tube and shell type or a cascade type. (XBL 7410-4450)

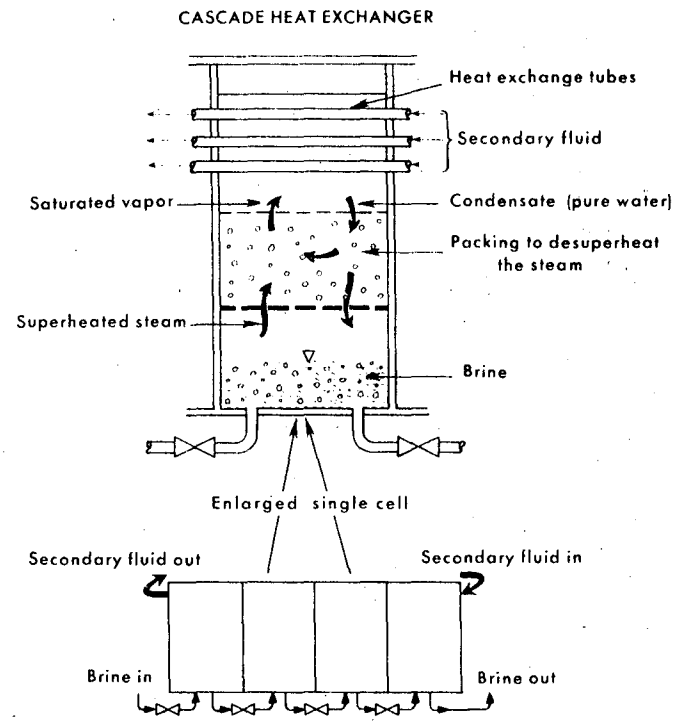

Fig. 3. A schematic diagram of a four stage cascade heat exchanger; detail of the stage is shown. (XBL 762-2242)

U factor in this heat exchanger could be as high as 3402 W $m^{-2}K^{-1}$ (600 Btu hr^{-1} ft^{-2} $°F^{-1}$). This could result in a reduced cost power plant.

Figure 3 is a schematic view of a four stage cascade heat exchanger. Table 2, which is divided into two parts, shows the temperature and pressure within the cascade heat exchanger stages as a function of brine concentration. Table 3 compares the performance of a simple bi-fluid cycle using the cascade heat exchanger with the cycle using the ordinary tube and shell heat exchanger.

The cases shown in Table 3 show how the computer handles NaCl solutions as a working fluid. The cascade heat exchanger and tube type heat exchanger involve no change in brine concentration. Some processes such as flash tanks and two-phase turbine expanders will involve changing the concentration of the brine by the removal of water to the gas phase. GEOTHM contains some iterative subroutines which will handle the changing brine concentration problem. Multiple flash cycles have been modeled on GEOTHM for proposed power plants at Niland and Heber in the Imperial Valley. This has been made possible by the development of a saline brine properties deck.

Table 2. State points within a four-stage brine to isobutane cascade heat exchanger for brine concentrations of 0 and 200,000 ppm.

A. FOUR STAGE CASCADE HEAT EXCHANGER

Stage number	Brine P (bar)	Brine T (°C)	Condensate T (°C)	Isobutane temperature (°C) Inlet	Outlet
1	27.95	230.0	230	163	220
2	12.54	190.0	190	135	163
3	4.76	150.0	150	95	135
4	1.43	110.0	110	40	95

Brine concentration	0 ppm NaCl by wt
Inlet brine enthalpy	1131.1 Jg^{-1}
Inlet brine temperature	280°C
Brine to isobutane flow ratio	0.832
Pinch point delta T	10°C

B. FOUR STAGE CASCADE HEAT EXCHANGER

Stage number	Brine P (bar)	Brine T (°C)	Condensate T (°C)	Isobutane temperature (°C) Inlet	Outlet
1	27.95	239.0	230	166	220
2	12.54	197.5	190	136	166
3	4.76	156.4	150	96	136
4	1.43	115.4	110	40	96

Brine concentration	200,000 ppm NaCl by wt (4.28 M)
Inlet enthalpy	919.5 Jg^{-1}
Inlet temperature	280 °C
Brine to isobutane flow ratio	1.057
Pinch point delta T	10°C

The net power yields shown in Table 3 are interesting because the four stage cascade heat exchanger does not fare well thermodynamically as compared to the tube and shell heat exchanger. Increasing the number of stages will improve the efficiency considerably. In both cases the 300,000 ppm brines cannot be cooled below 158°C without the NaCl coming out of solution. The cases in Table 3 are idealized but they show that salts in the water in a geothermal field will have a detrimental effect on plant performance aside from the obvious fouling and corrosion problems found in systems using saline brines.

Table 3. The net electrical energy per unit well flow as a function of brine concentration.

Brine concentration (ppm)	Net electrical energy yield (W hr/kg) Four stage cascade heat exchanger	Tube and shell heat exchanger
0	26.673	35.145
100,000	23.189	30.968
200,000	20.995	28.398
300,000	15.066[a]	------[b]

[a]This is a three stage heat exchanger, the fourth stage would fill up with salt.

[b]NaCl would come out of solution plugging the heat exchanger.

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THE KINETICS OF QUARTZ DISSOLUTION AND PRECIPITATION

J. A. Apps, E. L. Madsen and R. L. Hinkins

Geothermal brines contain silica which is normally saturated with respect to quartz at the temperature of the enclosing rock formation. This silica can precipitate when the brine is cooled, either in the geothermal power plant or in the formation in which the brine is subsequently injected. Convection of the brine within the geothermal reservoir also results in dissolution, transport and precipitation of silica, leading eventually to formation sealing at the reservoir boundaries.

At the present time none of these processes have been adequately investigated. It is not known whether the potential problems caused by such processes will be severe or inconsequential. However, their importance to utilities planning to exploit geothermal power is very great. The management of a utility does not wish to be in the position of having made substantial investments in plant construction only to discover that the plant is subject to repeated fouling, or that the injection wells are continually plugging and require expen-

sive rehabilitation.

In order to provide quantitative answers to these problems, this project has been initiated in 1975 specifically to investigate the kinetics of silica dissolution and precipitation.

The objectives of the project are: (1) to determine what deleterious effects will result from rapid withdrawal of hot water and reinjection of spent fluids in a convecting reservoir, and (2) to formulate equations to predict the rate of scaling in geothermal power plant components.

ANNUAL ACTIVITIES

During 1975 the principal effort involved the acquisition of data on quartz and amorphous silica dissolution in the aqueous phase, development of a theory to explain the observed dissolution behavior, and evaluation of the data in terms of the theoretical mechanism. As a result of this study, further tasks are planned for 1976 to refine our knowledge of kinetic mechanisms of silica dissolution and precipitation and to verify these mechanisms through experiment. A detailed description follows:

Theory

Using absolute rate theory,[1] an a priori assumption is made that the mechanism of silica deposition involves the following reaction:

$$SiO_2 + 2H_2O \underset{k_b}{\overset{k_f}{\rightleftharpoons}} C^* \underset{k_b}{\overset{k_f}{\rightleftharpoons}} Si(OH)_4 \qquad (1)$$

where $\frac{k_f}{k_b} = K_f^*, K_b^*$ (2a)

and $K_f^* = \frac{[C^*]}{[SiO_2][H_2O]^2}$; $K_b^* = \frac{[C^*]}{[Si(OH)_4]}$ (2b, 2c)

C^* = the activated complex

K_f^* and K_b^* = the equilibrium constants relating the activated complex with the reactants and product respectively.

Now $\frac{dn_f}{dt} = \frac{\kappa kT}{h} [C^*] A\sigma$ (3)

$$= \frac{\kappa kt}{h} K_f^* [SiO_2][H_2O]^2 A\sigma \qquad (4)$$

κ = transmission coefficient
n = moles of SiO_2 going into solution
k = Boltzmann's constant
T = Absolute temperature
h = Planck's constant
A = Surface area
σ = Surface site density

let $\frac{\kappa kT}{h} K_f^* = k_f'$ (5)

where k_f' is the specific forward rate constant.

Substituting (5) in (4)

$$\frac{dn_f}{dt} = k_f' A\sigma[SiO_2][H_2O]^2 \qquad (6)$$

by analogy

$$\frac{dn_b}{dt} = k_b' A\sigma[Si(OH)_4] \qquad (7)$$

Net rate of change

$$\frac{dn_f - dn_b}{dt} = k_f' A\sigma[SiO_2][H_2O]^2 - k'_b A\sigma[Si(OH)_4] \qquad (8)$$

By assuming the activities of the silica and water to be unity, and the activity coefficient of $Si(OH)_4$ to be unity, Eq. (8) can be integrated and reorganized to yield:

$$\frac{n}{m} = \frac{n_o}{m} e^{\frac{-A\sigma k_b' t}{m}} + \frac{k_f'}{k_b'} \left(1 - e^{\frac{-A\sigma k_b' t}{m}}\right) \qquad (9)$$

where m = mass of solvent
n_o = initial mass of $Si(OH)_4$

Data Aquisition and Evaluation

The available literature on the kinetics of dissolution and precipitation of quartz and amorphous silica in the aqueous phase was reviewed. Unfortunately, few studies have been made which present information of sufficient quality to evaluate using Eq. (9). Most of the data involve the dissolution or precipitation of quartz in water. Some data are available covering the kinetics of dissolution of quartz in sodium hydroxide or sodium chloride solutions. Evaluation of sodium hydroxide data was not carried out, because of the need to interpret the data in terms of additional dissolved silica species. Only one experiment on the precipitation of amorphous silica was useable.[2]

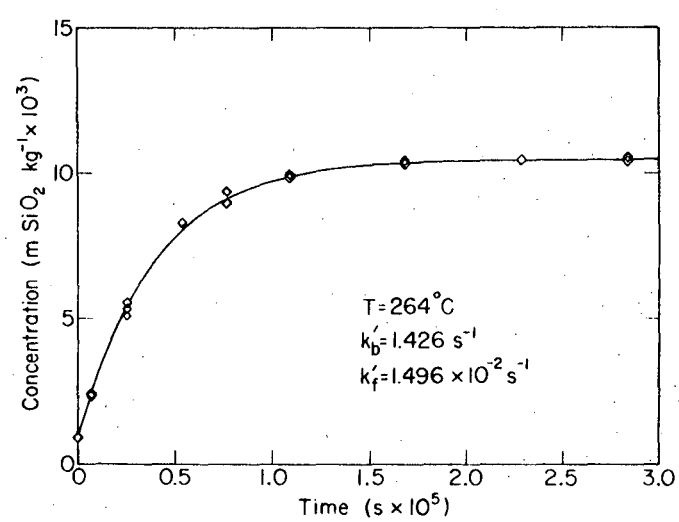

Fig. 1. The dissolution of quartz in water at 264°C. The data are from Kolvoord and Yorgason[3]. The solid line represents the best fit to the data using Eq. 9. (XBL 767-3228)

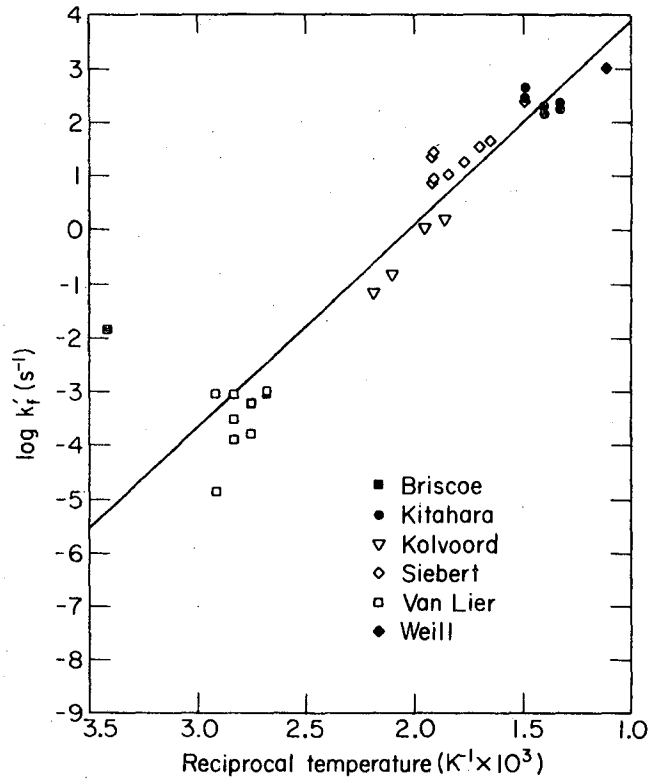

Fig. 2. The logarithm of the specific forward rate constant, k_f' for the dissolution of quartz in water, plotted against the reciprocal of the absolute temperature. The values k_f were calculated from data by Briscoe et al.,[4] Kitahara,[5] Kolvoord and Yorgason,[3] Siebert et al.,[6] Van Lier et al.[7] and Weill and Fyfe.[8] (XBL 767-3230A)

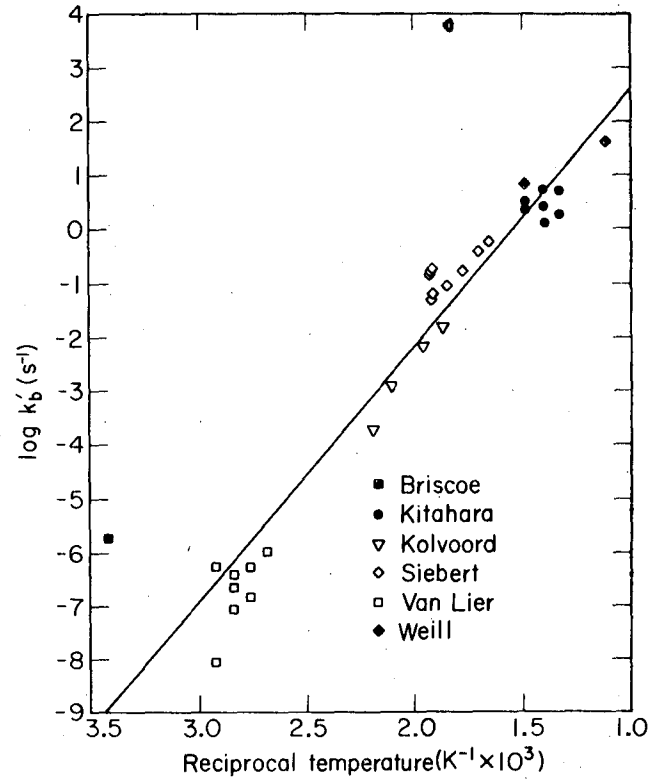

Fig. 3. The logarithm of the specific back rate constant, k_b', for the dissolution of quartz in water, plotted against the reciprocal of the absolute temperature. The values of k_b' were calculated from data by Briscoe et al.,[4] Kitahara,[5] Kolvoord and Yorgason,[3] Siebert et al.,[6] Van Lier et al.[7] and Weill and Fyfe.[8] (XBL 767-3232A)

Equation 9 was fitted to selected experimental data in which k_f', k_b' and n_o were variable, and values of k_f' and k_b' and n_o obtained. An example, of an excellent fit, using data of Kolvoord and Yorgason[3] is given in Fig. 1. Arrhenius plots of k_f' and k_b' for quartz dissolution or precipitation in water were made of data from several sources,[3-8] as illustrated in Figs. 2 and 3. A straight line, fitted to the data yields activation energies of 21.8 and 17.2 kcal/mole respectively for the dissolution and precipitation reactions. The computed equilibrium constants assuming $k_f' / k_b' = K$, for reaction (1) are shown in Fig. 4. The computed values for k_b' and k_f' from the 25° C data of Briscoe et al.,[4] do not correspond to the observed trends established by higher temperature experiments. This suggests that other mechanisms of silica dissolution and precipitation may prevail at lower temperatures. A possibility is the adsorption of a monolayer of SiO_2, as has been suggested by Stöber.[9]

The striking feature of quartz dissolution and precipitation kinetics is the large rate constant change between 25°C and 350°C. Data for the dissolution and precipitation of quartz in NaCl solutions were insufficient to justify detailed analysis. However, they do suggest that the presence of NaCl in solutions up to 0.1 mole/kg does not affect the rate of quartz dissolution by much more than a factor of 10. At higher temperatures, the effect may be even less.

Because only one set of data on amorphous silica dissolution is available, no information could be obtained regarding the variation in rate of amorphous silica precipitation as a function of temperature.

Conclusions

1. The equation developed (Eq. 9) on the *a priori* assumption that the mechanism of silica dissolution and precipitation is represented by the reaction

$$SiO_2 + 2H_2O = Si(OH)_4$$

is consistent with most quartz dissolution and precipitation data. However, the actual reaction may be more complicated.

2. Although there are sufficient data to observe the trends in quartz dissolution and precipitation kinetics, the data are too variable in quality and insufficient in quantity to estimate the rates accurately.

3. Data describing quartz dissolution in NaCl solutions are insufficient to draw any firm conclusions regarding the influence of NaCl concentration on quartz dissolution kinetics.

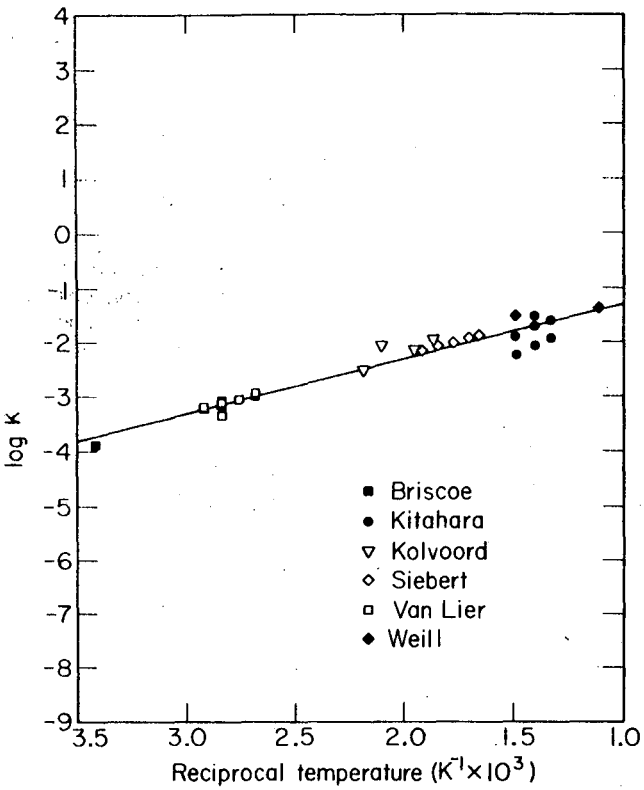

Fig. 4. The logarithm of the equilibrium constant K, for the dissolution of quartz in water, plotted against the reciprocal of the absolute temperature. The values of K were calculated from data by Briscoe et al.,[4] Kitahara,[5] Kolvoord and Yorgason,[3] Siebert et al.,[6] Van Lier et al.[7] and Weill and Fyfe.[8]

(XBL 767-3231A)

4. No information is available that permits evaluation of the precipitation or dissolution of amorphous silica over the range of temperatures of interest.

5. The large changes in the rates of quartz dissolution kinetics are reflected in the use of the silica geothermometer in spring waters to determine temperatures at depth. It is evident that the so-called quartz geothermometer must in fact register temperatures at which the rate of equilibration of the dissolved silica with the environment becomes slow with respect to the cooling rate of the water.

6. At 25°C and below, quartz dissolution rates become so slow, as to be almost impossible to determine experimentally. It is possible that other mechanisms, such as adsorption tend to interfere.

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PHYSICAL MODELING OF GEOTHERMAL RESERVOIRS

V. E. Schrock

In this program we are conducting laboratory experiments on thermal convection in porous media. These experiments serve two important purposes in the total research on reservoir dynamics:

(1) They provide reliable experimental results for use in testing and validating numerical computational methods and computer codes.

(2) They provide the basis upon which model laws can be studied and verified. Eventually, when we have refined the method sufficiently, experiments aimed at directing physical modeling of actual reservoirs may prove to be a useful tool.

To accomplish these objectives, it is necessary to experiment with a variety of geometries, medium characteristics and thermal and hydrodynamic boundary conditions. Our first series of experiments have been carried out in a sand bed in a

rectangular enclosure 1.1 x 1.85 x 1.2 meters. Water is pumped out of the sand bed through a horizontal porous ceramic tube, cooled by a controlled amount in an external heat exchanger and then reinjected into the sand bed through a second parallel porous tube. This configuration was chosen as a simple rough simulation of geothermal extraction and reinjection. It was designed to produce two-dimensional fields of fluid motion and temperature for comparison with 2-D codes. Initially the sand bed was isothermal. The boundaries of the box were impermeable and were maintained adiabatic. The results of such an experiment reveal the interplay between the forced convection (due to pumping) and natural convection brought about by fluid denisty changes. Tests have been made for a range of parameters such as pumping rate, temperature difference and sand bed permeability such that data have been obtained for cases ranging from strong to negligible natural convection.

The temperature distributions that develop are important in gaining an understanding of the effectiveness of energy removal. Although the tests so far conducted are very simple we think this approach will eventually lead to an understanding of more complex systems of wells and the ability to design optimum energy extraction methods. A paper based upon some results is currently in press.[1]

A second series of experiments is now underway to study the effects of heating the bottom of the bed and cooling the top. Convection cells are being studied in the absence of pumping and this will be followed by superposition of the two. When these tests are completed we plan to carry out experiments in anisotropic media with horizontal stratification of permeability.

A portion of the research is aimed at identifying scaling laws for designing and interpreting model experiments.

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

W. H. Somerton

INTRODUCTION

Objectives of this project are to develop methods of and equipment for the measurement of properties and behavior of rock-fluid systems at environmental conditions of pressure, temperature and fluid saturation that may be encountered in geothermal power development and thermal recovery methods applied in the extraction of fossil fuels. These data are needed in the interpretation of well logs in relation to zonal evaluation, in the study of fluid and heat flow in relation to subsurface reservoir management, and in prediction of well bore stability and possible surface effects associated with fluid withdrawal from the reservoir.

Methods of measuring the desired properties and equipment capable of making such measurements to temperatures as high as 200°C and pressures of 1000 bars were developed through earlier projects.[1,2] Support for this project from the Lawrence Berkeley Laboratory began in FY 1974. Design work is in progress on a new test facility capable of measuring all the desired properties concurrently on the same test specimen to temperatures as high as 500°C and pressures to 1250 bars. Design problems and materials limitations have necessitated modifications in measuring methods and the development of new methods in some cases. The present test facilities are being used for testing these methods and for a continuing program of obtaining data on a widening variety of rock-fluid systems within the limits of the equipment.

ACTIVITIES DURING 1975

Design of the new test facility was completed to the point where actual construction will be necessary before final design details can be worked out. New features of the apparatus include an internal split-cylinder radiant test specimen heater, water cooling in regions of measuring components, seals, and signal lead outlets, an axial cylindrical electrode for resistivity and thermal conductivity measurement, and use of alumina AD-85 for transmitting sonic signals and to provide electrical and thermal insulation. Actual construction is awaiting funding from sources as yet unknown.

A new laboratory in Room 120 Hesse Hall has been partitioned and provided with services for the apparatus.

Wave velocity studies have shown that temperature decreases both shear and dilatational wave velocities and that the ratio of the two velocities V_s/V_d is a good indicator of vapor-liquid contacts at any pressure and temperature. This is due to the fact that liquid saturation affects the velocities in opposite directions. Knowledge of both shear and dilatational velocities improves the accuracy of intrinsic strength estimations that are used in borehole stability studies.

The effects of temperature on decreasing permeability and increasing formation resistivity factor

have been confirmed. Plugging problems in permeability measurements have been virtually eliminated by improved water treatment and handling and by use of ultra fine filters. The cylindrical electrode method, using the metal sheathing as the outside electrode, has given good results although further testing is needed.

Thermal expansion tests on dry rocks from a geothermal test well showed the strong effect of quartz content. Low quartz content samples showed about half the thermal expansion of quartz-rich specimens. Thermal expansion tests on liquid saturated specimens are now in progress. Application of the present test methods for both thermal expansion and compressibility in the new apparatus must await construction and preliminary testing to determine suitable reference locations.

Thermal conductivity tests were run on the suite of samples from a geothermal test well mentioned above. The steady state apparatus was used for these tests. The strong effect of quartz content mentioned above was also noted in these measurements. Work on the thermal conductivity model was nearly completed. Good agreement between model and test results was obtained, minimizing the importance of including a liquid-solid contact resistance term in the model. Work was continued on the measurement of liquid-solid contact resistivity. Although experimental results indicated the existence of such a resistance, the possible presence of a thin film of adsorbed air on the solid surface or a small amount of gas coming out of solution from the liquid upon transient heating, could not be disproved.

PLANS FOR 1976

Further progress on the design and construction of the new apparatus must await location of a funding source. In the meanwhile the pressure vessels and the pressure console used with the present apparatus will be moved into the new laboratory.

The Arenberg pulse generator will be repaired and modified to greatly increase the strength of sonic signals. Shear and dilatational transducers will be stacked on the alumina AD-85 loading cylinders and velocity measurements of fluid saturated rocks will be continued.

Permeability, formation resistivity factor, thermal expansion and compressibility testing will be resumed with the relocated and redesigned test apparatus. Hopefully some geothermal test-well cores will become available for testing.

Thermal conductivity testing will be continued using the existing steady-state apparatus. The prediction model will be completed and tested against all experimental results. Further development of the needle probe method of measuring thermal conductivity will be a priority matter. Manufacture of the probe, the outer stainless steel sheathing of which will serve as the resistivity electrode, may present some problems, but a commercial manufacturer will be consulted.

Work on the liquid-solid contact resistivity problem will be completed early this year. Work will be resumed on determination of conductive heat transfer coefficients for liquids flowing in porous media.

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RESULTS OF RESERVOIR EVALUATION TESTS, 1975 RAFT RIVER GEOTHERMAL FIELD, IDAHO

T. N. Narasimhan and P. A. Witherspoon

INTRODUCTION

On a request from the Idaho National Engineering Laboratory (INEL), the Lawrence Berkeley Laboratory Geothermal Group was asked to provide assistance in assessing the size and producing capabilities of the geothermal reservoir in the Raft River geothermal area near Malta in southeastern Idaho. Between January and August, 1975, INEL had drilled two geothermal wells 4990 and 5990 feet deep respectively and successfully tapped artesian water at approximately 295°F. The aim of the LBL project was to conduct flow tests on the two wells and make preliminary estimates on the reservoir parameters and geometry to help in further exploration and development of the reservoir.

RESERVOIR ASSESSMENT

Location and Geology

The Raft River Valley is located in southeastern Idaho (Fig. 1), about 160 miles northwest of Salt Lake City. The valley, which historically used to be at the intersection of the Humboldt River Trail to California and the Oregon Trail, is hemmed on the west, south and east by hill ranges and is open towards the north. The valley is about 15 miles wide in an east-west direction, is over 40 miles long and is at an elevation of about 4800 feet while the surrounding mountains rise to over 9000 feet.

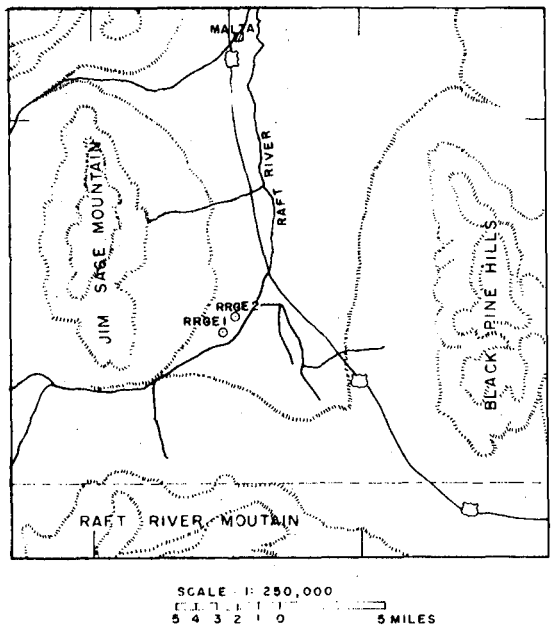

Fig. 1. Location map of Raft River Valley Geothermal Field, Idaho.
(XBL 764-2839)

Table 1

	RRGE 1	RRGE 2
Total depth, feet	4,989	5,988
Casing		
Diameter, in.	13-3/8	13-3/8
Depth, ft.	3,624	4,227
Uncased hole		
Diameter, in.	20	12-1/4
Depth range, ft.	3,624-4,989	4,227-5,988
Major Production, Depth range	3,624-4,200 (?)	4,227-5,000 (?)
Reservoir Temperature, °F (°C)	≈294 (146)	≈294 (146)
Well Head Pressure	≈150 psi	≈150 psi

Geologically, the Raft River Valley is located close to the junction of two great geological structures, namely, the Basin and Range province on the south and the Snake River Plain on the north. The valley itself is a north-south trending structural depression which is considerably faulted. The floor of the valley is apparently a westward-tilted down-faulted block.[1]

The structural depression or the "graben" of the valley is filled with sediments ranging in age from Tertiary (the Salt Lake formation) to Quaternary (the Raft River formation), with a total thickness of about 6000 feet. The Salt Lake formation comprises sandstones, silts and tuffs while the Raft River formation consists of over 1000 feet of alluvial, fluvioglacial and lacustrine silts, sands and gravels. The floor of the depression containing the sediments is formed by a precambrian quartz monzonite, an igneous rock chemically allied to granite.

Description of Wells

The two geothermal wells, RRGE 1 and RRGE 2 are located in Section 23, Township 15 South, Range 26 East. The distance between the wells is approximately 4000 feet with RRGE 2 being northeast of RRGE 1. The completion data for the two wells are given in Table 1.

Careful geological study of the drilling data indicated that RRGE 1 penetrated a fault zone between 4250 and 4630 feet below ground level. No such fault zone could be recognized within RRGE 2 down to a depth of 5988 feet.

Reservoir Tests

The basic aims of the reservoir test were to evaluate the permeability and storage parameters of the reservoir and to decipher reservoir geometry. The tests essentially consisted in producing fluid from one of the wells at controlled rates and over prolonged periods of time and observing the water pressure changes in the producing well itself or in the other well. Since the wells have positive well head pressures (artesian), controlled flow can be achieved by carefully opening the well head valve. Also, since the theory of the tests is based on a single, homogeneous fluid, the flow had to be so controlled that there can be no flashing or formation of a vapor phase within the well.

Since the wells are about 4000 feet apart, the pulse introduced at one well can create only very small pressure changes in the observation well. A key piece of equipment in the tests was therefore a very sensitive quartz crystal pressure gage that can be conveniently lowered into the well to any desired depth and which communicates with a surface recording equipment through a conductor cable. The pressure gage has a resolution of 0.01 psi (over the range 0 - 10,000 psi) and can withstand temperatures of up to 300°F.

Details of the Tests

In all, three tests were conducted between September 12 and November 7, 1975. Two of these were production well tests in which the pressure gage was positioned in the production well within the producing interval. This was necessary in order to ensure a fairly stable temperature environment for the pressure gage, which is temperature sensitive. The production well tests were both of short duration and lasted less than 30 hours. After shutting down production, pressure buildup within the well was monitored for approximately 24 hours.

The third test was an interference test in which fluid was produced from RRGE 2 and the pressure changes were monitored in RRGE 1. Since the latter was quiet and fluid filled, it was not essential to position the instrument close to the

Table 2

Test No.	Description	Duration Hours	Production Well No.	Production Flow Rate	Pressure Gage in Well No.	Pressure Gage in Depth, feet	Maximum Pressure drop Well No.	Maximum Pressure drop Δp, psi
1	Short Term Test	15	RRGE #2	225 gpm	RRGE #2	5200	RRGE #2	39
2	Long Term Test on RRGE #2	615-1/2	RRGE #2	400 gpm	RRGE #1	1000	RRGE #1	3.6
3	Short Term Test on RRGE #1	30	RRGE #1	26 gpm	RRGE #1	4700	RRGE #1	1.1

bottom of the well. The interference test, which provides data on a large portion of the reservoir between the two wells, was of a long duration. During this test, RRGE 2 was flowed for approximately 26 days.

The specificiations of the tests conducted are given in Table 2.

RESULTS AND INTERPRETATION

Before we present and discuss the results it is pertinent to briefly state the theoretical bases of interpretation. The analytical model used for interpretation is that of transient potential distribution around a continuous line source (axisymmetric system) in an infinite, homogeneous, horizontal slab of finite thickness. By the principle of superposition and using image concepts, the model can be extended to non-infinite or bounded systems. Details of this interpretative technique can be found in Witherspoon et al.[2] or Ferris et al.[3] The aim of interpretation is to determine the reservoir permeability, transmissivity, kH, the reservoir capacity, ϕcH and decipher the existence of barriers or other boundaries. The transient pressure change around a line source in an initially static system is given by the relation[2] (often called the Theis[4] equation)

$$\Delta P = \frac{q\mu P_D}{(v)\ kH} \tag{1}$$

where ΔP is pressure change, q is constant flow rate, μ is fluid viscosity, P_D is dimensionless pressure, V is a constant depending on units used, k is permeability and H is reservoir thickness. Moreover, P_D is given as an integral of the dimensionless time t_D

$$P_D = 1/2 \int_u^\infty \frac{e^{-u}}{u}\, du \tag{2}$$

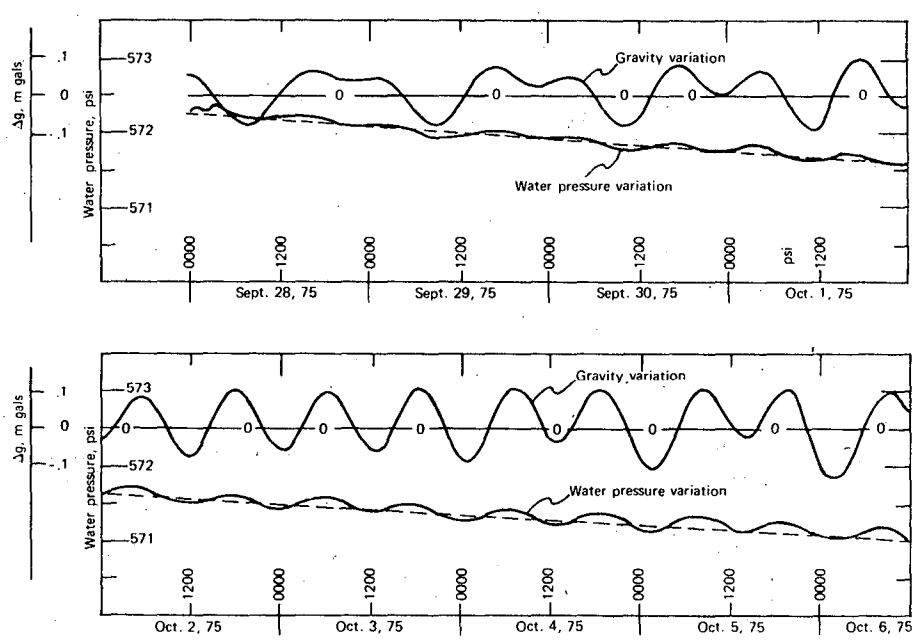

Fig. 2. Effect of earth tides on water pressure in RRGE 1, Raft River Valley, Idaho. (XBL 764-2837)

where $u = 1/4\ t_D$. The dimensionless time t_D is given by

$$t_D = \frac{kt}{\phi\mu c r^2} \qquad (3)$$

in which t is time, ϕ is porosity, c is compressibility of the porous medium and r is the radius to the point of observation. In order to evaluate kH and ϕcH using (1), (2) and (3) a technique of curve matching[2,3] is conventionally used by plotting the pressure drawdown data on log-log paper. Or, for $t_D \gg 1$, an asymptotic approximation may be used in which drawdown is plotted as a function of the log of time. In addition to obtaining kH and ϕcH, the departure of the plotted data from the type curve in the log-log plot or the occurrence of breaks in the straightline segments of the semi log plot would indicate the presence of barrier or leaky boundaries in the system.

Influence of Earth Tides on Fluid Pressures

A significant fact that came to light during the interference test was that the fluid pressures in the reservoir respond systematically to the changes in the earth's gravitational field induced by the paths of the moon and the sun. The field data indicated regular oscillations with a period varying from 10 to 12 hours and with amplitudes of up to 0.1 psi about the mean.

For a proper evaluation of the pressure data, the gravitational changes at the location of RRGE 1 over the period of the test was calculated by Dr. Howard Oliver of the U.S. Geological Survey, Menlo Park, California. Figure 2 is a comparison between the calculated gravity variation and water pressure variation in RRGE 1 between September 28 and October 6, 1975. It can be seen from the figure that there is good correlation between gravity change and pressure change. Careful examination of the data showed that the troughs and crests of the water pressure wave tend to lead the corresponding features of the gravity wave in general by 15 to 45 minutes. As we will see from the subsequent section on interpretation, due consideration had to be given to the tidal influence before the interference data could be analyzed.

The Production Tests

As seen from Table 2, two production tests were conducted, one each on RRGE 1 and RRGE 2. Both these tests were of relatively short duration. The test on RRGE 2 indicated a kH of about 47,500 millidarcy[5] feet and a ϕcH of about 3×10^{-2} psi^{-1}. The data indicated the probable existence of a barrier boundary very close to the well. The production test on RRGE 1 indicated a kH of about 110,000 millidarcy feet and a ϕcH of about 2×10^{-2} psi^{-1} in the vicinity of that well. In both these cases, the computed values of ϕcH are uncertain due to ambiguities in defining the effective well radius.

The Interference Test

As can be seen from Fig. 2, the interference test data were considerably masked by pronounced earth tide effects. As a first approximation to eliminating the tidal effects and aiding in the interpretation, advantage was taken of the fact

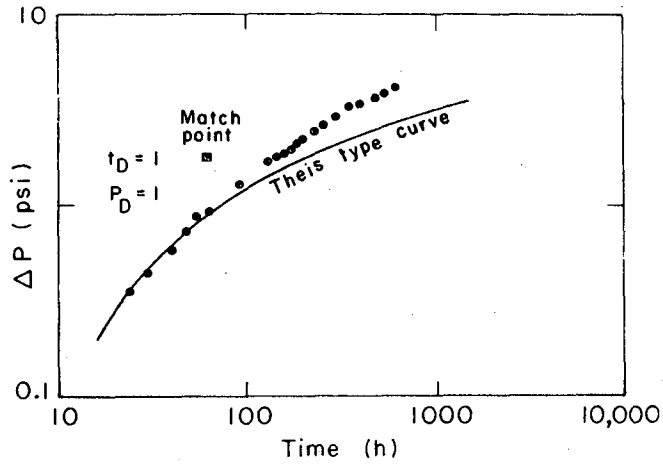

Fig. 3. Interference test, RRGE 1: log-log plot of time vs. drawdown.
(XBL 764-2838)

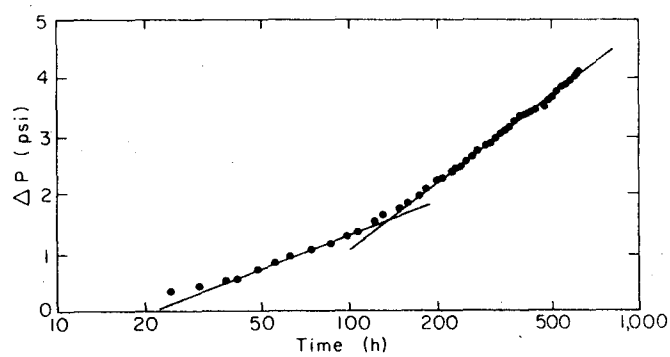

Fig. 4. Interference Test, RRGE 1: semi-log plot of time versus drawdown.
(XBL 764-2835)

that the gravity and pressure waves are almost in phase. Hence only the pressure readings at those instants of time when gravity change was zero were used for plotting and interpretation.

The log-log and the semi-log plots of time versus drawdown are shown in Figs. 3 and 4. It was computed that the portion of the reservoir between RRGE 1 and RRGE 2 has an overall kH of about 193,000 millidarcy feet and a ϕcH of about 1.1×10^{-3} psi^{-1}. The departure of the observed data from the type curve in Fig. 3 after about 100 hours and the prominent break in the slope of the straightline segment in Fig. 4 both suggest the presence of a barrier boundary. Calculations indicate that the existing barrier is equivalent to an "image" production well located about 11,000 feet from RRGE 1. However, with only two wells available, it is impossible to uniquely locate this image well and precisely fix the position of the barrier boundary.

Conclusions

The calculated value of nearly 200,000 millidarcy feet for kH from the interference test sug-

gests that the geothermal reservoir in the Raft River Valley is significantly permeable and hence merits further exploration and study. The indication of barriers suggests that in certain directions the reservoir may be limited. However, the continuity of the reservoir between RRGE 1 and RRGE 2 over a distance of 4000 feet indicates that the reservoir is of considerable dimensions. In order to be able to effectively define the location and orientation of barriers or other boundaries, it will be necessary to have one or more suitably located additional wells.

PLANNED ACTIVITIES

Further exploratory work is being actively carried out in the Raft River Valley by the INEL. A third well, RRGE 3 is expected to be drilled by the end of April 1976, at a location about 1.2 miles southeast of RRGE 1, towards the center of the valley.

The LBL Geothermal Group is in close touch with the INEL and more production and interference tests are proposed to be carried out between May and July 1976, in order to gain in improved knowledge of the promising geothermal reservoir.

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5. 1 millidarcy = 9.67×10^{-7} cm/sec.

RADIOACTIVITY AND METAL MINERALIZATION

H. A. Wollenberg and Alan R. Smith

The natural terrestrial radiation environment is dominated by the gamma-radioactivity from ^{238}U, ^{232}Th, and ^{40}K in rocks and soil. The radioelements are concentrated according to the magmatic differentiation series, being of lowest abundance in ultramafic and basic igneous rocks and greatest in felsic rocks such as granite and rhyolite.

The terrestrial gamma-ray field can be measured by sensitive scintillating detectors, based on a crystal of thallium-activated sodium iodide (NaI(Tℓ)). NaI(Tℓ) values are normally read as counts per second, directly convertible to microroentgens per hour. More advanced systems incorporate a scintillation detector connected to a portable single-channel pulse-height analyzer which can resolve the different gamma-ray energies characteristic of the radioelements. This type of system permits assay, on the outcrop, of the U, Th, and K contents of the material beneath or surrounding the detector. The advantages of field assays may be outweighed by the long time required to obtain a statistically significant number of counts to properly analyze the individual radioelements. A portable gamma-rate-meter may be more useful, in that nearly continuous measurements of the total gamma-ray field are an excellent parameter for control of sampling. Samples are then analyzed in the laboratory for their radioelement contents.

There is a possibility that gamma radiometry may be useful as a guide to metal mineralization. The relationship between field gamma-radioactivity and mineralization in metal deposits was demonstrated by Moxham et al.[1] and more recently by Davis and Guilbert.[2] In traverses of porphyry- and vein-type deposits in Arizona they observed increased count rates from potassium associated with hydrothermal alteration minerals (sericite, chlorite) in country rock of the ore zones. The main variations were in K. Uranium and thorium were relatively constant, indicating no correlation with alteration zones. Thus, total gamma-radioactivity reflecting potassium may be indicative of mineralization.

This was tested in the Summer of 1975 by surface and underground traverses of altered and unaltered areas of country-rock rhyodacite at the mines of Cia. Minas Buenaventura at Julcani, Peru, where the principal product is silver. Instrumentation consisted of a 3-in. diameter by 3-in. thick NaI(Tℓ) detector, coupled to a count-rate meter. Readings were made continuously as the party walked along the underground drifts and on the surface. Counting rates underground varied from 500-600 counts per second in unaltered rhyodacite, to over 1100 counts per second in areas of alteration surrounding the ore vein. Surface readings, significantly lower than underground

because of geometry factor, showed similar relative differences in counting rates between altered and unaltered areas. In most cases, the ore bearing veins themselves were of relatively low radioactivity in contrast to the altered wall rock.

Samples were taken, and analyzed by laboratory gamma spectrometry, to see which radioelements reflect hydrothermal alteration in the Julcani area.

When K content is compared with the gamma-ray counting rate, there is a positive correlation for surface and underground samples, while there are no apparent correlations between U and Th content and counting rates; indicating that variations in gamma radioactivities at Julcani reflect, primarily, variations in K content of the rocks. Therefore, results of radioelement analyses corroborate the supposition that high radioactivities reflect the relative enrichment in potassium associated with zones of hydrothermal alteration associated with ore mineralization.

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"ARMS" AND "GEODOSE"

H. A. Wollenberg and J. Fitzpatrick

In support of the on-going surveys by the Aerial Radiological Measurement System (ARMS), operated by EG&G Inc. for the Division of Operational Safety of ERDA, we conducted radiogeologic studies of five reactor sites in the eastern U.S. Sites covered in brief reports to EG&G were:

Big Rock Point, on the east shore of Lake Michigan;
Crystal River, on the Gulf Coast of Florida;
Edwin I Hatch, on the Altamaha River, Baxley, Georgia;
Scriba, New York, on Lake Ontario; and
Three Mile Island on the Susquehanna River, Pennsylvania.

The objective of the studies was to furnish information on the geologic setting of the sites that would influence planning and interpretation of the aerial gamma-radiometric surveys. Relative radioactivities were predicted on the basis of the distribution of rock and soil types. Flight lines were oriented to best take advantage of the lithologic and structural "grain" of the site regions. Follow-up studies will compare gamma-aeroradiometric patterns with site-region geology.

To facilitate the prediction and follow-up comparison of rock types with observed radioactivities, a project* called GEODOSE was started in the latter half of 1974. The objective of the GEODOSE project is to characterize rock and soil types by their natural gamma-ray exposure rates. The geochemical literature is being searched for data on K, U, and Th contents of earth materials, and these data are categorized by rock type, based on standard petrologic classifications. A data bank is being assembled, with incorporation of radio-element information on the igneous rocks essentially completed. Metamorphic and sedimentary rock data are presently being compiled. The data are treated to produce computer plots of histograms of K, U, Th contents, calculated gamma-ray exposure rates, and radiogenic heat production for given rock types. Accompanying these plots will be means, standard deviations, and ranges of the parameters. Initial processing of data for igneous rocks indicates that alkaline and peralkaline terranes have generally the highest gamma-ray exposure rates, and suggests that alkaline and peralkaline rocks are probably associated with most of the broad areas of highest natural radioactivity. A summary report was prepared[1] and presented at the International Symposium on Areas of High Natural Radioactivity, Pocos de Caldas, Brazil in June 1975. Figure 1, from that report, illustrates the frequency distribution of gamma-ray exposure rates for acidic intrusive rocks.

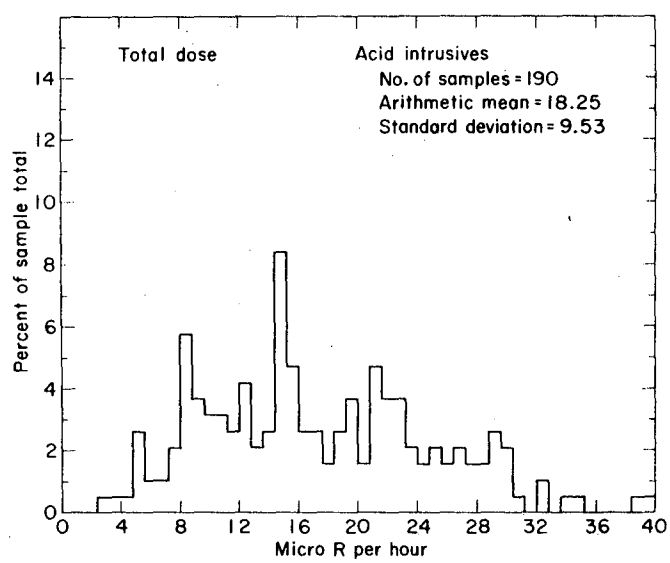

Fig. 1. Frequency distribution of total gamma-ray exposure rates for acidic intrusive rocks. (XBL 755-3015)

FOOTNOTE AND REFERENCE

*Project funded by EG&G Inc.

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INVESTIGATION OF RADON-222 IN SUBSURFACE WATERS AS AN EARTHQUAKE PREDICTOR

*A. R. Smith, H. R. Bowman, D. F. Mosier, F. Asaro, H. A. Wollenberg and Chi-Yu King**

INTRODUCTION

Recent reports of Chinese and Russian earthquake-prediction efforts[1] indicate that radon-222 in subsurface waters may respond to changes in earth strain which precede earthquakes. Such changes are also reflected in some characteristics of crustal rocks within and near epicentral areas, for example: variations in the ratios of compressional and shear wave velocities, and apparent electrical resistivity. It is postulated that dilatancy of rocks in response to strain may enhance release of ^{222}Rn from the rocks into the ground water regime. Thus the onset of seismic activity may be preceded by an increase in the radon content of well and spring waters in the vicinity.

We summarize here the initial progress in a collaborative effort between the University of California Lawrence Berkeley Laboratory (LBL) and the National Center for Earthquake Research of the United States Geological Survey (USGS) at Menlo Park. The intent of this work is to develop a compact high-precision real-time continuous monitor system for field measurement of ^{222}Rn in subsurface waters, an instrument that could serve as a prototype for a network of such stations. Data from a group of these stations could then be coordinated with other geophysical information related to earthquake precursors, to be used in earthquake prediction.

Although the work described here focuses on the γ-ray spectrometric method, application of α-particle detection to this purpose is also being vigorously pursued, especially by the USGS side of the collaboration, as reported at the December meeting of the American Geophysical Union in San Francisco.[2]

THE CONTINUOUS MONITORING TEST FACILITY AT LBL

The prototype continuous monitoring station has been in operation at LBL since April 1975, functioning as a test facility to evaluate the measurement technique and system performance. A γ-ray spectrometer counting the γ-rays emitted by the daughters of ^{222}Rn provides a stable and rugged system with the capability for continuous monitoring at high sensitivity.

The LBL system includes a NaI(Tl) crystal detector located centrally in a tank through which radon-bearing water flows, a multichannel pulse-height analyser (PHA) with digital gain stabilization, and peripheral units that record digital quantities derived from the gamma spectrum. A tank size of 3- to 6-ft diameter and equal height is adequate; a 3-in diameter by 3-in thick NaI(Tl) crystal provides ample sensitivity for the relatively low-activity LBL water (100 to 300 c/min) depending upon selection of the energy interval. The channels are integrated over selected energy regions at 10 min intervals and recorded. Precision of 1% or better is easily attained by summing several such intervals, permitting measurement of a few percentage change in ^{222}Rn abundance in a small fraction of a day.

The water source for the LBL station is from a horizontal hole drilled approximately 400-ft into the hillside for slope-stabilization purposes. The drain hole provides a constant flow rate of about 1.5 gal/min with a ^{222}Rn content of $\sim$300 pCi/liter. The daughter products of ^{222}Rn decay (the source of the observed γ-radiation) are greatly depleted in water that flows from this hole. Note that it is not practical to measure ^{222}Rn directly by γ-detection, but rather by detection of γ-rays from the two daughters ^{214}Pb and ^{214}Bi. The effective half-life for ingrowth of these daughters is approximately 40 minutes; thus our ^{222}Rn measurement technique must take into account a period of time lasting as long a 5 hours in which the daughters and ^{222}Ra may not be in equilibrium. This is the case for ^{222}Rn entering the detection volume without any daughters, i.e., ^{222}Rn that is either just created or freshly stripped of the daughters. This nonequilibrium problem may be expected as a general characteristic of natural aquifers,[3] and must be taken into account when designing flow-through measurement systems.

THE DISCRETE SAMPLING PROGRAM

Discrete sampling of well water is an integral part of the program ranging in application from reconnaissance studies in new areas, through long-term support in the vicinity of a continuous monitoring station, to exclusive use in long-term surveillance in a study area. These samples consist of groups of 2 to 7500-ml capacity polyethylene bottles. The container was chosen for its inherent low radioactive content, acceptable

small loss of radon by diffusion through the container walls and purity with respect to trace element contamination.

All discrete samples are transported to LBL and are assayed for ^{222}Rn by γ-ray spectrometry, assuming equilibrium with the daughters, where we utilize a high-sensitivity NaI(Tℓ) system located in the Low Background Counting Facility and the Health Physics Department. The low background counting environment is necessary for the successful measurement of the small ^{222}Rn family activities present in most water samples.

THE OROVILLE AREA: STUDIES DURING AN AFTERSHOCK SEQUENCE

An earthquake of Richter magnitude ∿6 occurred near Palermo in the Oroville area of the Sierra Nevada foothills (about 120 miles northeast of San Francisco) on August 1, 1975. We established a discrete sampling program for water wells on August 5, and a continuous monitoring station at one well at the Palermo Elementary School on August 27-28. We sought to take advantage here of the large number of aftershocks in an effort to establish whether our techniques could demonstrate a relationship between ^{222}Rn levels in well waters and seismic events, given the particular geologic terrain of the Sierra foothills and a limited selection of already existing relatively shallow wells in the epicentral area.

At present we obtain samples from six wells, four in the Sierra foothill metavolcanic bedrock formations and two in the Tertiary sedimentary deposits of the eastern margin of the Sacramento Valley. Sampling (on at least a daily basis) is done almost entirely by the local residents, without whom this part of the study would be impossible.

From mid-September onwards, intervals between aftershocks lengthened sufficiently so that we could begin to attempt correlations between changes in

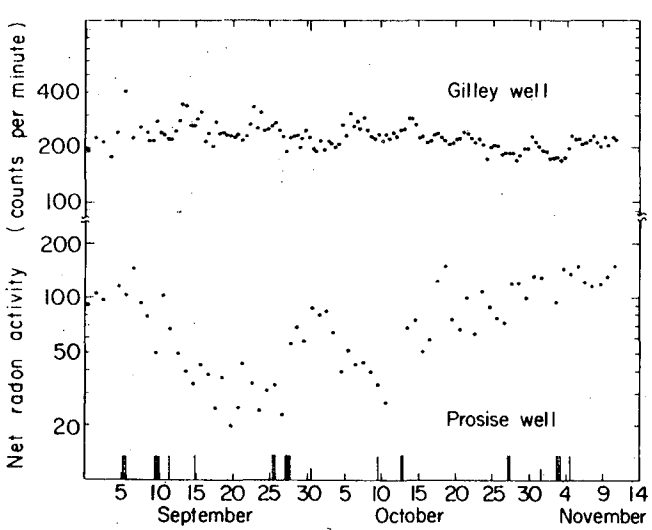

Fig. 1. Results of ^{222}Rn measurements in the discrete sampling program from two bedrock wells in the Oroville area. (XBL 7511-9520)

^{222}Rn levels and seismic activity. Data from two of the bedrock wells for this period are shown in Fig. 1, where the laboratory analyses are expressed in terms of decay-corrected ^{222}Rn counting rates. The occurrence times of aftershocks with Richter magnitudes greater than 2 are indicated along the base line of Fig. 1 as the tallest vertical bars.

Some preliminary comments are given here to illustrate the current understanding of the data from the discrete sampling program. The two wells (Fig. 1) exhibit marked changes in radon abundance as a function of time, but in contrasting patterns. For example, the low/high/low structures in Gilley well data from the periods September 21-24 and October 4-8 may be related to the aftershock sequences of September 25-27 and October 10-13. The high/low structures in the Prosise well data may be related to these same aftershocks, although the time scale appears to be quite different. The Gilley well data also show a general decrease in ^{222}Rn levels throughout this period, in a continuation of a trend observed since early August, and generally following the decrease in frequency of aftershocks. Data from the Gilley and Prosise wells show less structure with passage of time from September to mid November.

There appears to be some general correlation between aftershock activity and the radon abundances in the bedrock wells; however, the aftershocks may still be too closely spaced in time to permit distinction between precursor and response signals. On the other hand, a well drilled into the Tertiary sediments at the Palermo School (data not shown here) has a much more constant radon level varying less than 25% during the same period. The discrete sampling program must continue into the period when the region is again seismically inactive, so as to establish base levels and normal variation patterns for ^{222}Rn content of these wells. Only then can the present data be completely evaluated to disclose which features were <u>most probably</u> related to seismic activity.

The continuous monitoring system at the Palermo School well was set up to measure the abundance of ^{222}Rn, using the school storage tank. Although discrete sampling had indicated the radon abundance in the water was nearly constant with time, marked variations in the apparent ^{222}Rn abundance were noted with the continuous system. These variations correlated closely with water usage patterns. For example, during periods of high use, the mean residence time in the storage tank was too short to achieve equilibrium between ^{222}Rn and daughters, and the observed count rate dropped considerably. An acoustic pickup was installed on the water system to indicate periods of pump operation, to permit possible recovery of the true radon abundance values from the data. The need for close control of water-flow patterns in such a continuous radon monitoring system was clearly demonstrated by this experience.

THE HOLLISTER AREA

In March 1975, preliminary survey in the

Hollister area of central California (about 100 miles south of San Francisco) disclosed the presence of ^{222}Rn in appreciable quantity at several wells; two wells at one site sustain considerable artesian flow during part of the year and also show relatively high ^{222}Rn content, approximately 800 pCi/liter. This site is in a zone of the San Andreas fault that is presently undergoing active tectonism in the form of abundant micro- and macro-earthquake activity and observable fault creep. It was chosen as the initial field station, to be occupied in the summer of 1975. However, occurrence of the earthquake near Oroville, California on August 1, 1975 caused postponement of establishment of a station in the San Andreas Fault zone until early November 1975.

The Hollister area is especially well suited for the ^{222}Rn study, not just because there are frequent small earthquakes, but primarily because here there are extensive instrumentation networks measuring geophysical parameters for the same purpose-sensing earthquake precursor signals. Thus the possibility exists to establish correlations between the ^{222}Rn method and several other methods, an opportunity not available in the Oroville area.

NEVADA TEST SITE STUDIES

A program of ground radon monitoring at the ERDA Nevada Test Site was started in September 1975 as an extension of the joint USGS-LBL study, in cooperation with Lawrence Livermore Laboratory (LLL) Test Division, the LLL Hazards Control Department, and the ERDA Nevada Operations Office. The purpose is to see if ground ^{222}Rn emanation is enhanced by the shock of underground explosions.

Two types of monitoring are employed. In one, discrete water samples are obtained at least weekly from deep wells that penetrate alluvium and sedimentary formations in the Yucca Flats area; these samples are sent to LBL for ^{222}Rn assay by γ-spectrometry. The second method employs radon alpha-track detectors, buried 1/2 meter deep in alluvium at distances ranging from 300 to 5000 meters from one particular shot point. The track detectors are changed weekly by LLL Hazards Control personnel. These detectors are provided, etched, and counted by Terradex, Inc. in Walnut Creek, California.

At the end of calendar 1975, neither the well samples nor the track detectors have indicated any clear response to the ground shocks associated with a number of underground explosions. However, the test shot for which the detector array was initially deployed was postponed until early 1976. The program is continuing to include this particular test, after which a report will be written to discuss the results of this study.

SUMMARY

Initial progress in the γ-ray detection method includes the following items. We have verified the major design features of a field station that performs continuous high-precision ^{222}Rn monitoring in water. We have established a long-term locally supported discrete well-water sampling program in the Oroville area during the period of aftershock activity, to investigate the link between ^{222}Rn levels and the ongoing seismic activity. Investigation is underway at the Nevada Test Site to determine whether there is a variation in ground radon abundance that may be linked to shock waves from large underground explosions.

FOOTNOTE AND REFERENCES

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3. Allan B. Tanner, "Radon Migration in the Ground, A Review," and "Physical and Chemical Controls on Distribution of Radium-226 and Radon-222 in Ground Water Near Salt Lake City, Utah," Chaps. 9 and 13 in The Natural Radiation Environment, edited by J.A.S. Adams and W.M. Lowder (University of Chicago Press, 1964).

SULFIDE LEVELS IN NATURAL WATERS: A POSSIBLE NEW GEOTHERMOMETER

Alvin J. Hebert

A previously described non-dispersive soft X-ray fluorescence spectrometer[1] has been used to determine sulfide levels in natural waters.[2] A modification of the original technique has allowed a factor of five improvement in reproducibility. The technique is applicable when the waters contain species other than sulfides, (such as sulfate), which do not produce observable interferences.

Experiments are performed with a highly homogeneous group of simultaneously silver plated copper disks that have been punched from the same

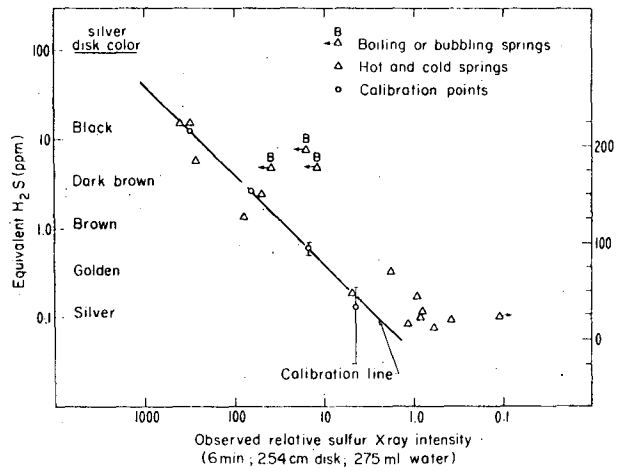

Fig. 1. Observed sulfur X-ray Intensities versus equivalent H_2S and also versus a linear Fournier-Truesdell (Na, K, Ca) geothermometer temperature or downwell reading (°C). (XBL 763-2527)

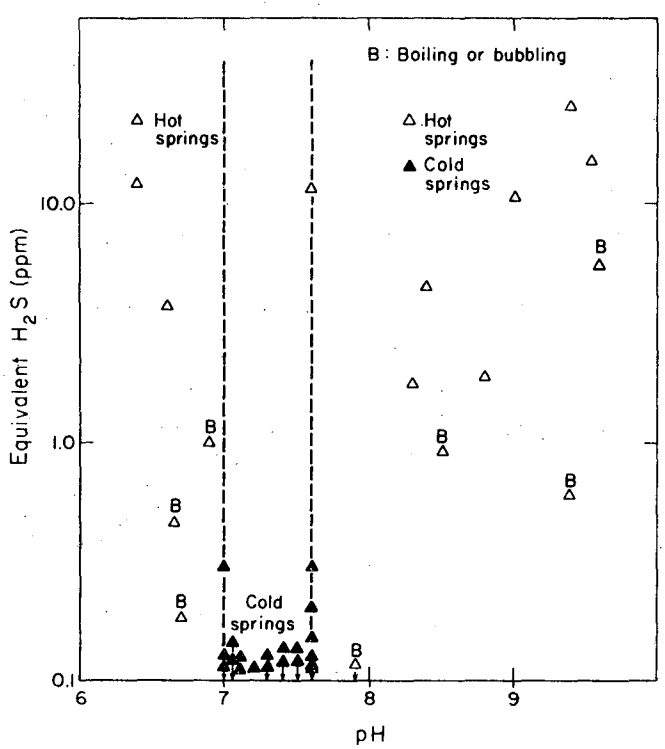

Fig. 2. A plot of pH versus Equivalent H_2S (ppm) for several North-Central Nevada springs. (XBL 763-2528)

sheet of copper foil. The disks are stored together in a plastic bag before use along with those to be used for calibration in the lab at the end of collecting each series.

The disks are brought into contact with water. After several hours, or days under actual field conditions, the aqueous sulfide level decreases by orders of magnitude. The water is weighed and may be used to calibrate the analysis or as a check for the effects of other species with respect to a distilled water calibration. Calibration disks are obtained by spiking distilled water samples with aliquots of a saturated solution of hydrogen sulfide in distilled water, and introducing a silver disk for one day.

A typical calibration line is shown in Fig. 1 along with a plot of Fournier-Truesdell geothermometer[3] (Na, K, Ca) temperatures calculated for some natural waters. A relative color scale is also indicated. It appears that when a hot spring has a flowrate of a few liters per minute or more, and if the water hasn't boiled or bubbled, good agreement with observed downwell or Na, K, Ca geothermometer temperature calculations are obtained. Boiling or bubbling causes outgassing and lowered sulfide levels in most cases. It also appears that a set of calibration point disks could be made and used for semi-quantitative sulfide determinations by visual comparisons. This would eliminate the need for soft X-ray fluorescence analyses.

Sensitivities for color-tone comparison experiments are expected to be of the order of 0.1 ppm at the 0.2 ppm level and a few ppm at the 10 ppm level. The use of multiple disks would maintain good sensitivity where the sulfide levels exceed 10 ppm.

Figure 2 is a plot of sulfide levels versus pH. Although the data appear scattered, it is important to note that all cold springs, as determined by the Na, K, Ca geothermometer, plot in the pH 7 to 7.6 range with sulfide levels at less than 0.2 ppm equivalent H_2S.

Both Fig. 1 and Fig. 2 indicate that the sulfide levels and the pH of natural springs may be of value in assessing the geothermal potential of an area.

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2. H. Bowman, A. Hebert, H. Wollenberg, and F. Asaro, A Detailed Chemical and Radiometric Study of Geothermal Waters and Associated Rock Formations, with Environmental Implications, presented at the Second International Conference on Nuclear Methods in Environmental Research, University of Missouri, Columbia, Missouri, July 29-31, 1974; H.R. Bowman, A.J. Hebert, H.A. Wollenberg and F. Asaro, Trace, Minor and Major Elements in Geothermal Waters and Associated Rock Formations (North-Central Nevada), presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, May 20-29, 1975.

3. A.J. Hebert and H.R. Bowman, Nondispersive Soft X-ray Fluorescence Analyses of Rocks and Waters, presented to the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, May 20-29, 1975.

A PORTABLE FIELD WATER SAMPLE FILTRATION UNIT*

Alvin J. Hebert and Gardener G. Young

The need for a lightweight back-packable filtration unit that could easily be cleaned without cross-contamination at the part-per-billion level while allowing rapid filtration of boiling hot and sometimes muddy water has given rise to the units shown on Fig. 1.

Field and laboratory tests indicate essentially no changes in carbonic acid or bicarbonate or carbonate ion concentratons when filtrations are done at approximately 1/3 atmosphere even though the pH value may range from 3.2 to 9.4.

Filtrations are performed by pouring the solution into the funnel or by placing a piece of tygon tubing down a well and drawing the water up and through the filter. Boiling water has been drawn up old geothermal well pipes as high as 5 meters in this manner. Filtration usually takes less than one or two minutes per 500 ml bottle when the water is not too muddy. During the filtration process, it is important that bubbles not be allowed in the input line, otherwise the unit will cease functioning properly until it is reopened and a new filter inserted.

Figure 2 shows the machined groove pattern of the main body teflon plate. These grooves are "round-bottomed" to facilitate cleaning. The tygon lines are connected to this plate with a small nylon nipple and viton O-ring to ensure vacuum integrity. A viton O-ring is placed in the large outer groove. A standard Millipore acetate filter (variety HAWP-142, 0.45 micron, 142 mm plain white filter sheet) is laid over the groove plate and viton O-ring prior to each clamp down and filtration. No separate filter support is necessary.

The eight central holes shown in Fig. 2 lead to the nylon nipple connector which fits into a mating recess on the other side. The main body teflon plates are backed by 1.27 cm thick aluminum plates.

The hand pump is manufactured by the Nalgene Labware Division of NALGE Sybron Corporation.

The legs on the unit are easily removed for packing. The end of the tie down bolts are expanded so that the brass butterfly nuts will not fall off.

The aluminum tubing sleeve shown in Fig. 1 on one of the 500 ml Nalgene bottles guards against bottle collapse when filtering very hot water. The snap-in nipples for line connections to the lid of the bottle were machined from nylon.

Total unit weight without lines or bottles is 3.5 kg.

FOOTNOTE

*Reference to this device has been made in the publications listed below.

H.R. Bowman, A.J. Hebert, H. Wollenberg, and F. Asaro, A Detailed Chemical and Radioactive Study of Geothermal Waters and Associated Rock Formations with Environmental Implications. Paper delivered at the University of Missouri-Columbia, Conference on Nuclear Methods in Environmental Research, July 29, 1974.

H.R. Bowman, A.J. Hebert, H. Wollenberg, and F. Asaro, Trace Minor and Major Elements in Geothermal Waters and Associated Rock Formations (North Central Nevada), presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May, 1975.

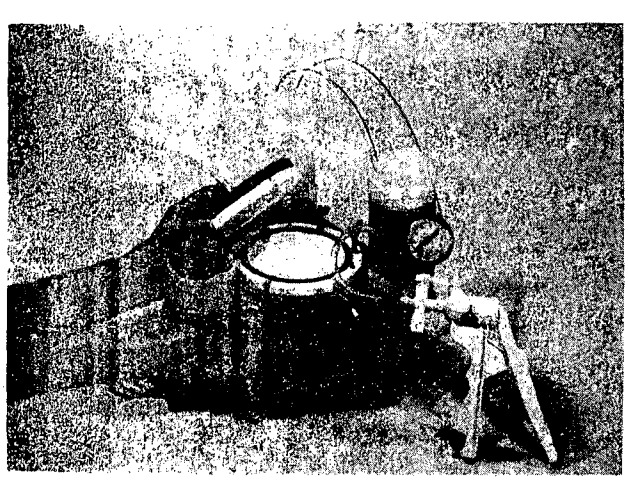

Fig. 1. Portable field water filtration unit. (BBC 7410-7355)

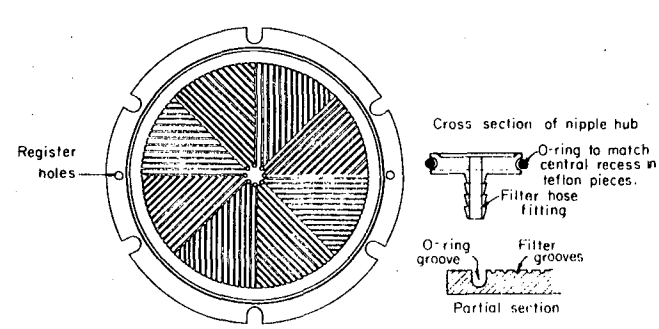

Fig. 2. Main body teflon plate. (XBL 758-3817)

Alvin J. Hebert and Harry R. Bowman, Nondispersive Soft X-ray Fluorescence Analyses of Rocks and Waters, in the proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May, 1975.

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EVIDENCE IN SUPPORT OF A HOMOGENEOUS SOURCE FOR ALKALIC BASALTS

H. Bowman, F. Asaro and I. Carmichael

Alkalic basalt lavas (basalt lavas with substantial amounts of the alkaline elements) are generally thought to be generated through partial melting of the upper mantle. Bacon and Carmichael[1] have shown that one of the lavas of these studies is consistent with this picture and could have equilibrated with mantle material at depths of approximately 75 km. Precise trace element measurement on these lavas and similar lavas from widely separated parts of the world suggest that these lavas were generated under similar conditions from sources of similar composition. A concurrent study of the large crystals (megacrysts) and mantle fragments included in some of these lavas has demonstrated that there are a number of elements in these lavas which can be used to test for the chemical composition of the source material in the mantle. Figure 1 shows a plot of two of these elements Ta and U from these widely separated geological environments. These data include over 20

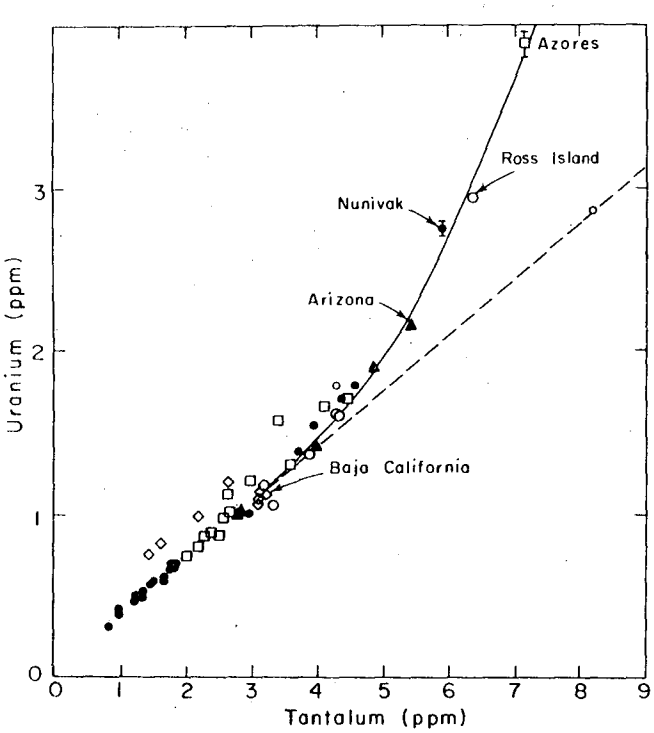

Fig. 1. Concentration of U vs Ta in alkalic basalt lava samples from the Azores, Nunivak Island, Ross Island, Arizona, and Baja California.

(XBL 767-3070)

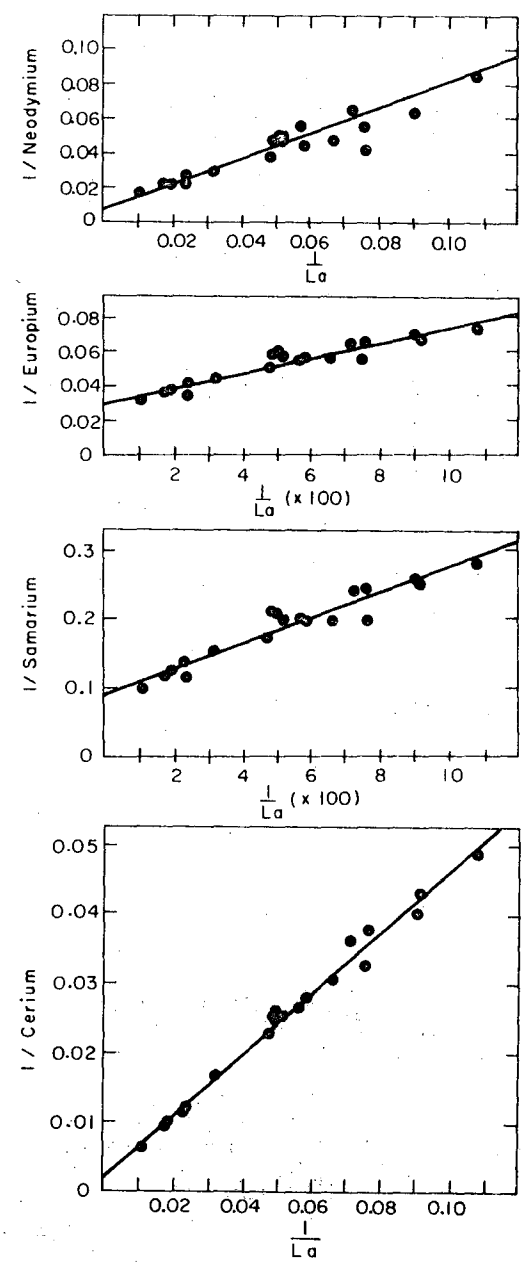

Fig. 2. Reciprocal concentration plots of several trace elements relative to reciprocal La concentration in alkalic basalt lavas.

(XBL 767-3071)

samples from Nunivak Island, off the Alaskan coast, erupted over a 6 month period, 15 historic eruptions from the Azores in the central Atlantic Ocean, a dozen eruptions in the southwestern U.S. and a series of samples from Ross Island, Antarctica. The general coherence between Ta and U and other trace and minor elements suggests a common source and generation process. In Fig. 2 we have plotted some of these element abundances relative to La as reciprocal concentrations to show how these data can be used to test for the composition of the mantle. If only a small fraction of the source material is melted and it is in equilibrium with the residual crystalline material then one can show that a plot such as Fig. 2 should produce straight lines with slopes related to the ratios of the mantle concentrations of these elements to the reciprocal mantle concentration of La. The vertical intercepts are related to the overall elemental partitioning coefficients between the melt and the residual minerals in the mantle.

The equation is:

$$\frac{1}{C_y} = \frac{C_{x_o}}{C_{y_o}} \frac{1}{C_x} + \frac{(K_y - K_x)}{C_{x_o}}$$

where C_y is the abundance of the trace element, y, in the melt; C_{yo} and C_{xo} are the weighted averages of the abundance of y and x in the mantle associated with the melt. C_x is the abundance in the melt of a specific trace element x (chosen for its low partition coefficient), K_y and K_x are weighted averages of the partition coefficients for the trace elements y and x between the mantle and melt. The equation presumes the averaged partition coefficients are essentially constant for the various melts.

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HIGH-TEMPERATURE PROPERTIES OF SILICATE LIQUIDS*

I. S. E. Carmichael

The heat content of a series of silicate liquids covering the whole known range of those found in nature has been measured by drop calorimetry in the temperature range 1200-1650K. From these and other published data, values of the partial molar heat capacities of SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O and K_2O have been derived, and apart from Fe_2O_3 show no compositional dependence. There is also no temperature dependence of the partial molar heat capacities in this temperature range.

FOOTNOTE

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NATIONAL GEOTHERMAL INFORMATION RESOURCE (GRID)

S. L. Phillips, J. A. Fair, F. B. Henderson and S. R. Schwartz

The main objective of GRID as an information analysis center is to provide critically evaluated and analyzed data to geothermal specialists (See Fig. 1). Our principal activities covered the following four areas: (1) compilation of geothermal exploration publications for the years 1974-1975; (2) compilation and evaluation of the thermodynamic and PVTX properties of NaCl solutions; (3) environmental aspects of geothermal utilization, and (4) adaptation of the Berkeley-Data Base Management System (BKY-DBMS) computerized data system for storage and retrieval of GRID information. A portion of these activities are described in more detail in Refs. 1-4.

As a pilot study, a report on the status of geothermal subsidence data was issued. The review is intended to provide quick referral to data of interest for the researcher engaged in assessing the effects of subsidence as related to the utilization of geothermal energy. It also contains a section noting either inadequate or currently unavailable data for topics that need further research, for example:

1. Development of a model that includes the important parameters for predicting geothermal subsidence: (a) rate of aquifer compaction as a function of fluid removal, (b) rate of land subsidence as a function of aquifer compaction, (c) effect of aquifer depth on land subsidence, (d) effect of recharge rate on aquifer compaction, (e) the relationships between aquitard structure and compaction.
2. Laboratory testing of rocks obtained at

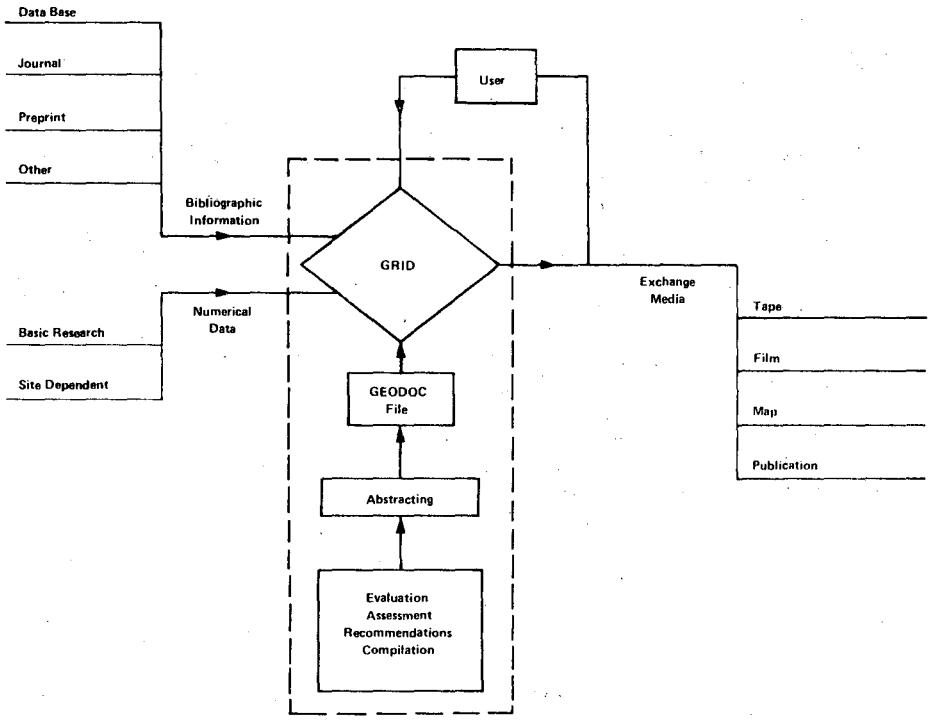

Fig. 1. (XBL 7610-4873)

depth to measure the rock compaction as a function of important parameters (e.g., porosity, water content, temperature, pressure). The tests will provide site-dependent data on compaction and the likelihood of subsidence, and can also be used to test the applicability of mathematical models.

3. Development of rock-sampling techniques at depth.

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