

WORKSHOP
ON
GEOHERMAL RESERVOIR ENGINEERING*

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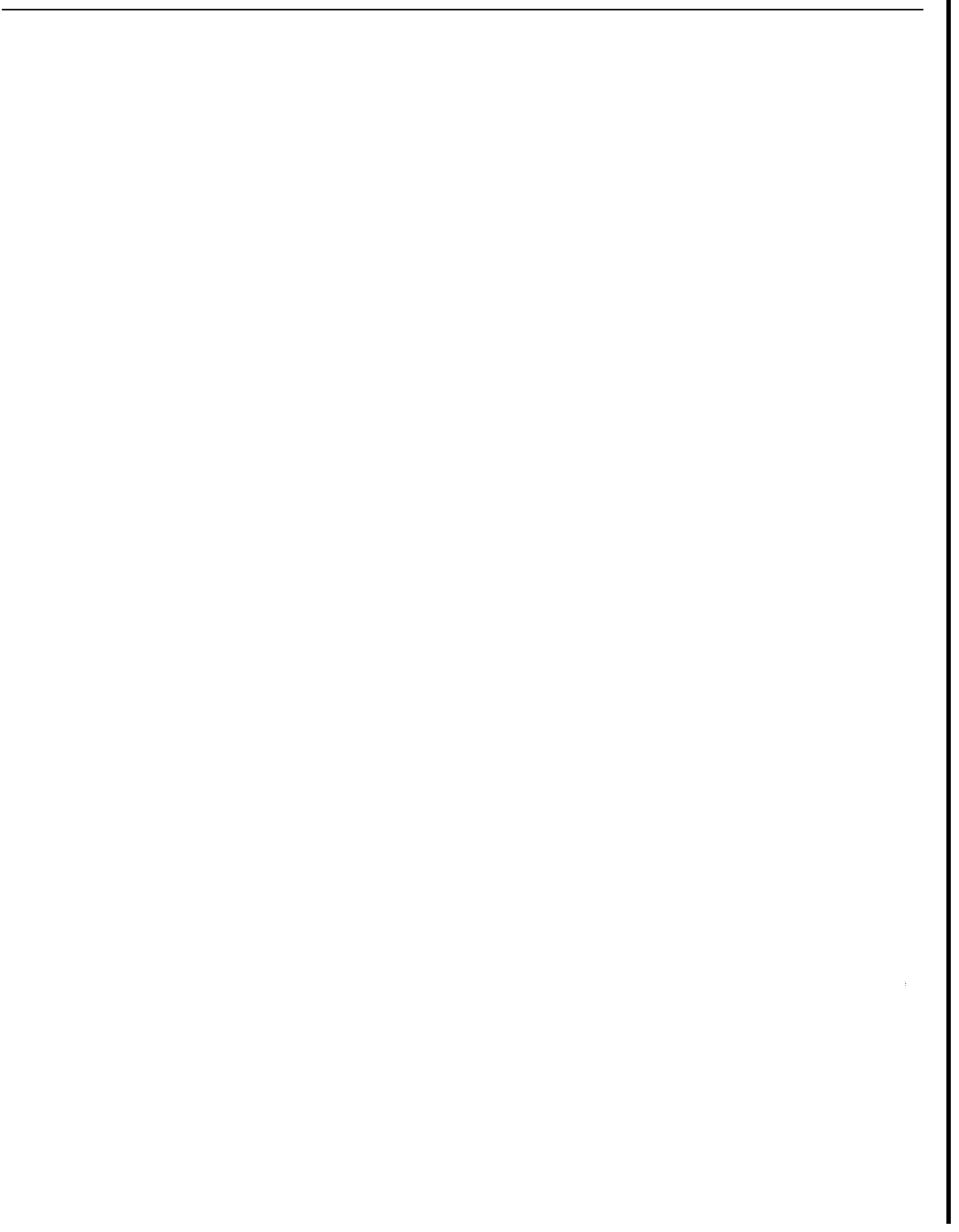


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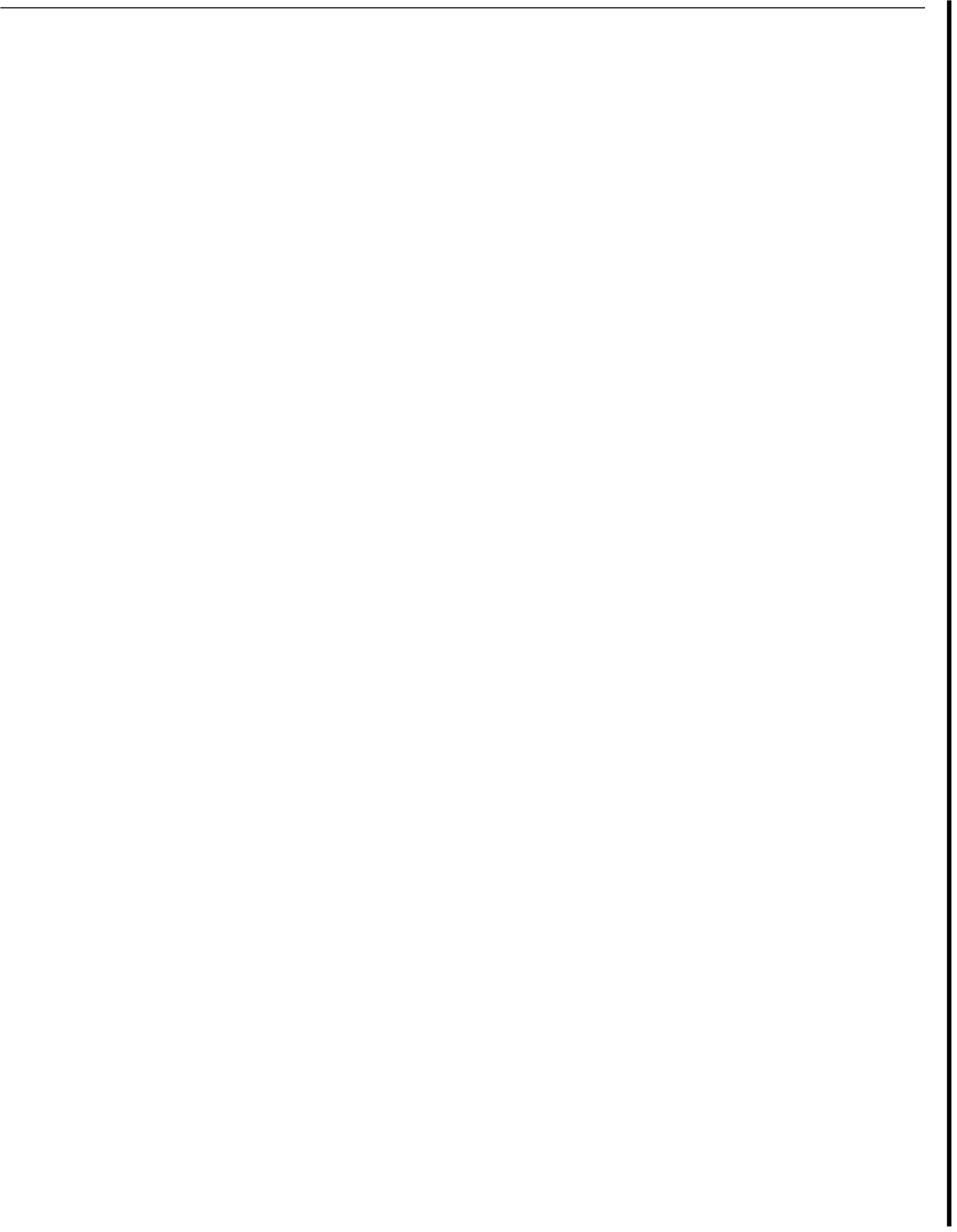
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INTRODUCTION

Although geothermal energy was first converted to electricity more than 70 years ago, until recently little public demand for its widespread use existed. Geothermal energy has been considered an attractive alternate source of energy for more than a decade in many developed as well as undeveloped countries and the international awareness of the growing deficit of fossil fuels has sparked accelerated interest in determining national resources and utilization technologies. As of 1976, the total world generating capacity for generating electricity from geothermal resources is about 1100 MW (equal to that of one modern nuclear power plant) and more than 3/4 of it is produced at only two sites, The Geysers in California and the Tuscany fields in Italy.

Many problems have been identified which beset the rapid development of geothermal resources, covering the entire "fuel cycle" from exploration through conversion and residuals control. The major problem is the inflexibility of natural geothermal resources which occur in a wide variety of hydrogeologic, thermal, and chemical qualities. Utilization must be designed to fit the specific characteristics of individual resources. Since the thermal efficiencies for conversion to electric energy are very low even for the two known highest quality hydrothermal resources, industrial development awaits greater economies in resource exploration and evaluation, energy extraction, and utilization technologies. To compound the problems, development is occurring in an era of increased public awareness about institutional and environmental concerns. As a result, a formidable array of legal, social, and regulatory problems also requires resolution.

As the development of a geothermal industry proceeds, these many problems are being evaluated generally by the sector of the national economy that has had experience in solving similar problems for other resources. The exploration for geothermal resources has been undertaken largely by the energy resource companies that use subsurface geosciences and the drill rig as their mode of operation. Conversion to electricity, presently the major utilization of geothermal resources, has been undertaken by the private and public utility industry. And the institutional problems are within the domain of the several levels of public administration ranging from the Federal government to county and township agencies.

It can be assumed that as the public demand for energy to be supplied by geothermal resources increases, accommodations between suppliers, regulators, and the public will be achieved. It can also be assumed that adequate technology will be developed to utilize "commercial" resources for both electrical and direct thermal applications. Thus, the major area for concern in the accelerated development of a geothermal industry is the definition of what constitutes a "commercial" resource. From a pragmatic point of view, a "commercial" resource is one from which a sufficient amount of geothermal resource can be extracted to sell to a willing buyer at a profitable price over some reasonable period of time.

Exploration for geothermal resources, in spite of the aforementioned institutional difficulties, is underway. Recent estimates by the U. S.

Geological Survey indicate a large number of potential areas of geothermal resources in the U. S. alone. The assessment of "commercial" viability of these resources is the difficult task, due in part to the small number of existing operational fields, and also in part to the empirical history of geothermal power plant development, with installation of generating capacity by one small unit at a time. It is clear from the many published forecasts of the potential for geothermal energy, ranging over orders of magnitude, that the actual resources (beyond the 1,000 to 2,000 MW probably existing at the one U. S. location) are essentially unknown. For undeveloped fields, uncertainties exist about the thermal quality of the resource, the heat and fluid extraction capability, the probable time history of deliverability and longevity, and the systematics for optimum development of the resource should it prove to be "commercial." All of the aspects may be considered to fall under the category of "Geothermal Reservoir Engineering," the topic of this Workshop.

Geothermal reservoir engineering has been an adaptive branch of engineering; much of the nomenclature and methodology have come from the oil and gas industry, from hydrology and hydrogeology, from the mineral industries, and from the basic physical, chemical, and nuclear sciences. In addition to the extensive efforts carried out by the operators in understanding specific reservoir characteristics, a national focus has developed on this important segment of the geothermal "fuel cycle," involving universities, industry, and the Federal government. Early efforts to develop the technologies of geothermal reservoir engineering were supported by the National Science Foundation and the U. S. Geological Survey. The Survey's program has been primarily an in-house program directed at describing what a geothermal resource is. Many contributions have been made in the classification and modelling of hydrothermal convective and geopressured systems. The National Science Foundation during its tenure as lead Federal agency for the accelerated development of geothermal resources initiated a series of grants to universities and research corporations to bring various disciplines together to build this branch of science and technology known as geothermal reservoir engineering. The newly-formed Energy Research and Development Administration has included such research in its overall program. Similar efforts are underway in other geothermal countries.

The purpose of the Workshop convened here at Stanford this December, 1975, is two-fold. First, the Workshop was designed to bring together researchers active in the various physical and mathematical branches of this newly-emerging field so that the participants could learn about the very many studies underway and share experiences through an exchange of research results. The second purpose was to prepare these Proceedings of the Workshop so that the integrated information could be disseminated to the geothermal community responsible for the development, utilization, and regulation aspects of the industry.

During the organization of the Workshop some seventy to eighty researchers active in the NSF program, the U. S. Geological Survey, and in university, industry, and ERDA national laboratories were identified by the Program Committee. Invitations to them and several individuals in nations active in this new field were extended. The major areas covered in the program consisted of reservoir physics (studies to evaluate the

physical processes occurring in geothermal systems), well testing (techniques used in specific and generic fields to determine the volumetric and extractive characteristics of a reservoir), field development (methods for the optimum development of producing fields), well stimulation (techniques for improving energy recovery from marginal hydrothermal and dry geothermal resources), and modelling (mathematical methods to study geothermal reservoirs).

The Workshop resulted in the presentation of 50 technical papers, summaries of which are included in these Proceedings. We hope that these summaries and the Rapporteur reports of the five sessions will prove valuable to our colleagues in industry, academic institutions, and especially to the government agencies responsible for an accelerated orderly development of our geothermal resources.

I wish to acknowledge the assistance of the Program Committee (R. Coryell, P. Kruger, M. Nathenson, H. Ramey, P. Witherspoon), the session Rapporteurs (P. Witherspoon, H. Ramey, G. Frye, M. Nathenson, J. Mercer), our colleagues from France, Italy, and New Zealand, whose participation enriched our program, the students in our Stanford Geothermal Program (P. Atkinson, H. Chen, A. Hunsbedt, and M. Kuo) who assisted in the workshop execution, and the National Science Foundation for its support and encouragement.

Paul Kruger
Stanford University
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RAPPORTEURS' REPORTS

SESSION 1 - RESERVOIR PHYSICS - Paul A. Witherspoon

Session I on Reservoir Physics included nine papers covering a wide variety of topics. Kassoy **summarized** the research activities currently underway at the University of Colorado, where attempts are being made to characterize and model the various processes that occur in geothermal systems. The importance of faults in controlling the convective motion within geothermal systems is being examined from a number of standpoints, and the effect of a realistic variation in viscosity on convection in porous bodies has revealed that the convective motion is unlike the symmetric classical profiles that result from a fluid of constant viscosity. A considerable effort is being made to develop a better understanding of the East Mesa geothermal system in the Imperial Valley.

Brigham reviewed the laboratory investigations currently underway at Stanford University to develop a fundamental understanding of non-isothermal boiling two-phase flow in porous media. One of the critical problems is how the normally immobile liquid saturations vaporize with pressure reduction under non-isothermal conditions. Recent work on the effect of temperature on relative permeability suggested that absolute permeability was also a temperature dependent property of rocks. Laboratory measurements have revealed that the temperature effect on permeability depends on the nature of the saturating fluid, whereas the effect of confining pressure on permeability seems to be independent of the nature of the saturating fluid. The objective of this work has been to simultaneously measure the effect of thermal and mechanical stresses on permeability. Brigham also summarized the advances that have been made in several directions in modeling geothermal fluid production.

Manetti summarized some recent work that has been carried out in Italy to correlate the kh distribution with geological structure at Larderello. Data from about 50 wells in different parts of Larderello were analyzed by back-pressure and pressure build-up methods. Good agreement between the kh values for any given well was only possible when the skin-effect was taken into account. A correlation of these results shows a good correspondence between areas of high transmissivity and the various structural highs within the Larderello field. The permeability is believed to reach its maximum values along the crests because tectonic activity has resulted in a maximum of fracturing and fissuring at such locations.

Martin presented a review of an analysis that **he** has made on internal steam drive in geothermal reservoirs that are produced by pressure depletion with no water injection. He compares the pressure-temperature behavior of geothermal systems and **shows** how they differ depending on the **initial** conditions. He concludes that under certain conditions only a relatively small

amount of the heat initially contained in a geothermal reservoir will be produced during pressure depletion. Where gravity segregation of the steam and hot water occurs during depletion, more of the total heat can be produced by completing wells high in the reservoir to enhance steam production and suppress water production.

Bodvarsson reviewed the analysis that he has been making of the "macro-permeability" that prevails in igneous rocks because of fracture conditions. From an analytical expression for flow to a horizontal fracture intersecting a borehole, he has analyzed the flow conditions that exist in fractured reservoirs. This approach has been used in Iceland to develop methods for testing wells, estimating reservoir permeability, and evaluating the results of well stimulation. Bodvarsson also discussed how the isotope chemistry of groundwaters in Iceland has been used to locate areas of recharge.

Natnenson summarized investigations that he has made to estimate the fraction of stored energy in hydrothermal convection systems that is recoverable. He has analyzed two possible methods for extracting energy: (a) boiling the water in the system to produce steam and (b) natural and artificial recharge of cold water to recover reservoir heat by a sweep process. It appears that the restricted range of porosity, temperature, and recharge over which the boiling method will work limits its application to rather special cases such as vapor-dominated systems. The fraction of stored energy that may be recovered is critically dependent on the average liquid saturation. In using recharging cold water to drive hot water to producing wells, conduction can be analyzed to a first approximation by superposition onto the movement of the temperature front. Another factor is the rotation of the initially vertical interface between cold and hot water. These processes can be combined qualitatively to yield an estimate of energy recovery.

Meidav presented a review of a method of using gravimetric data to estimate hydrothermal reservoir characteristics at the East Mesa geothermal field in California. Six positive gravity anomalies are associated with abnormally high temperature gradients in the Imperial Valley, and one of these anomalies is at East Mesa. The explanation for these observed effects is densification of the shallow sediments by deposition of temperature-sensitive minerals in the upward rising plume of geothermal waters. An excess mass of about 10 billion tons of matter is believed to have been deposited at East Mesa which would have required an upwelling of an estimated 2.5 trillion tons of thermal water. Assuming a period of 50,000 years was required leads to the conclusion that the vertical permeability ranges from 0.6 to 60 millidarcies. Although surficial evidence of geothermal activity is absent at East Mesa, this analysis sheds light on the very large underground movements of thermal waters that are possible when hydrogeological conditions do not favor outflow to the surface.

Tsang summarized an analysis he has recently made on screening geothermal production wells from the effects of reinjection. In the normal method of reinjecting cold water into a geothermal reservoir, breakthrough eventually occurs depending on several factors. In the simplest case of a doublet, one production and one injection well, this breakthrough time can be lengthened considerably by placing a screening well between the two wells

so as to intercept the shortest stream line. By producing water from the screening well, not only can breakthrough be delayed, but a significant increase in energy recovery can also be achieved. A detailed economic feasibility study of the effects of screening has not yet been made.

Garg reviewed the work that he and his colleagues are carrying out in an effort to mathematically model land surface subsidence associated with geothermal energy production. This is potentially a serious problem, particularly for liquid-dominated geothermal systems. The theoretical model, developed within the framework of the Theory of Interacting Continua, describes the thermomechanical response of the rock and fluid composite material in terms of the isolated components. The stress-strain equations for the rock matrix are coupled with the diffusion equations for the fluid. The microscale details of the pore/fracture network in the rock are ignored, but the fluid pressures and the stress field in the rock matrix are permitted to assume distinct values within each computational region for the composite. Although most of the required material properties can be obtained from standard laboratory tests on cores, it should be noted that the reservoir behavior is frequently governed by fractures, formation inhomogeneities, and other large scale features such as faults. It, therefore, becomes important to supplement the laboratory measurements by suitable field data. An example of some preliminary results in modeling a hypothetical subsidence problem was presented.

SESSION 11 - WELL TESTING - Henry J. Ramey, Jr.

Data from nine different field tests were presented. This one fact sets this session apart from all previous meetings or workshops. The field cases considered ranged from vapor to liquid-dominated reservoirs, and liquid-dominated systems ranged from low to high salinity systems. The types of well tests included pressure buildup and drawdown, and interference testing. As a result, it appears the state of development and application of the technology is good. Application of existing petroleum engineering and groundwater hydrology theories were shown to reveal the need for new solutions, however. Problems identified include:

1. New solutions for transient well testing (both interference and individual well tests) in hot aquifers which contain a carbon dioxide gas cap. The solutions should consider either production of hot water from down-structure wells, and production of carbon dioxide from upstructure or gas-cap wells. What properties are detected in such tests?
2. New solutions are needed for partially-penetrating wells in a tall steam column supported by boiling of a deep liquid interface. All types of tests should be evaluated.
3. Studies should be aimed at the results of flashing in the reservoir rock and resulting non-condensable gas evolution.

Another finding was that there hasn't been much supported research in the area of well test analysis. Work to date has involved mostly a rereading of existing information. Some work has been underway as a joint project by ENEL of Italy and personnel of the Stanford Geothermal Program.

During the presentations, a plea for field data was made and several participants responded (Roger Stoker of the Raft River Project, and Alain Gringarten concerning data from the Afars and Issas Territory).

Significant findings were made as a result of the presentation of much field data. It is clear that geothermal reservoirs are fully responsive to all pertinent laws of physics. A careful study of field performance results will often indicate important factors which should be included in computer simulation models. Field data presented at the workshop indicated: (1) there are well testing equipment needs, and (2) there were important recent findings as a result of application of new instruments. One need for new equipment concerned running pressure recorders into very high velocity steam wells while producing. There is a need for pressure and temperature recorders which can withstand both high vibration and high temperatures. Fluid production rates on the order of one million pounds per hour were cited in several cases!

Very interesting earth tide effects were cited as measured with high-precision quartz crystal pressure recorders in the Raft River project. Pressures were measured to 0.001 psi. This high precision represents a major step forward. However, the device is limited to upper temperatures in the range of 300°F to 350°F. The Hewlett-Packard system was used in the Raft River project. However, the Sperry-Sun stainless capillary tube system has been used a few times, and it appears that a combination of the capillary tube with a quartz detector in an insulated chamber at the surface might have immediate use in some geothermal wells.

Finally, several important observations from the Geysers Field were made. Burmah has observed water entry below a steam entry in two separate wells. Water samples were obtained, and it appears that the first significant information on the deep liquid interface postulated by Ramey, Bruce, and White may have been obtained. Another important observation was reported from the current Shell well drilling at the Geysers. Hydrogen sulfide concentrations as high as 3000 ppm were observed. This part of the well was plugged and the well sidetracked. Both the Burmah and Shell wells are in the eastern portion of the Geysers Field.

Throughout the discussions of various field well tests, it became obvious that most reporters considered presence of fractures common to geothermal reservoirs. As a result it appears that a "holistic" approach via well testing was usually necessary. Most field tests were characterized by a dearth of conventional electric log and core data. Well test analysis is an important technology that has largely been neglected to date. Because of the potential importance of this technology, one major finding of the workshop was identification of the need for more work in this area.

SESSION 111 - FIELD DEVELOPMENT - G. A. Frye

The authors present a maturing approach to field development. As mentioned in the opening session, the birth of geothermal reservoir engineering is accomplished and this session reflects early childhood development. Many authors express a cautious optimism about geothermal energy potential. Considerations about optimal energy extraction rather than concerns about economical production reflect this optimism. Several times the authors express the need for engineering design data and improved correlations from geophysics and well testing. Even though the geothermal energy field is relatively young in the United States, comments such as "I would have done it differently if I had to do it over again," indicate development of geothermal reservoir engineering.

Specifically the discussion sessions after the presentations reflected the needed development of high temperature, high resolution tools for greater confidence and shorter observation periods. Reinjection will be extremely dependent on anisotropic features of the reservoir found by these tools. Hinrichs discussed Magma's efforts in Imperial County to obtain data for establishing optimum production and injection techniques. He then introduced Mr. James Nugent of San Diego Gas and Electric Company (SDG&E) who presented the efforts of SDGEE and now along with ERDA on the geothermal test facility associated with the Magma wells. In some cases the geophysical analyses of economic fields can be expanded to new prospects. Wooding, while recommending this approach, cautioned that the same geophysics don't necessarily yield the same well test. More correlation between well test data and the geophysical data are required. Gould presented the task TRW Systems and the Bureau of Reclamation has assigned to Intercomp. The initial phase of this assignment involves analysis of current geophysical data in consideration of five wells on East Mesa operated by the Bureau of Reclamation. Later phases of this study concern reserves, field development and injection. Intercomp is also working with Republic Geothermal on the north end of East Mesa.

Another thrust of the discussion expressed concern about the length of time and initial capital investment that characterize electrical power production from geothermal energy. While not specifically field development, Woitke discussed PG&E's relationship with steam developers. The schedule for The Geysers development is typical of Burmah's experience. Also presented were two items now causing some concern or delay in field development at The Geysers. The first was a status report on H₂S abatement. Since this presentation, PGEE has made additional commitments to abate existing plants before development is expanded. The second item expressed an investor-owned utility's concern about certain Federal leasing regulations. Unless these concerns are resolved in a timely manner, power plant construction may be delayed. Comments such as the need to optimize the cost per kilowatt-hour and not maximize total energy recovery reflect this concern. Kuwada cautioned in his presentation that some optimal field development for energy may not minimize production

problems. Specifically there is an early requirement that the effects of dissolved gases and solids be considered. Scherer's approach to optimal rate of energy extraction appears to apply not only to geothermal developers, but also to governmental agencies as a planning guide.

Also expressed was the need for valid data for economic models and reservoir stimulators. Dorfman expressed the need for modeling of geopressured prospects to know how to best produce geopressured fluids. However, he pointed out there is limited published data on flow characteristics of these fluids for model validation. Some sensitivity analysis and examination of methodology is required to obtain assured forecasts from reservoir stimulators. Knutsen of BPNL presented Bloomster's paper. Preliminary results indicated the most important variables that determine the cost of geothermal energy.

SESSION IV - WELL STIMULATION - Manuel Nathenson

The stimulation of geothermal reservoirs involves techniques for artificially creating higher permeability in the region near a well over a distance of a few centimetres to an order of 10^3 m. Current geothermal practice involves hydraulic pumping to reopen producing horizons clogged during drilling, to remove vein deposits, and to fracture to a minor extent the region very near to the well (Tomasson and Thorsteinsson, 1975). Current research concerns massive hydraulic fractures and the creation of rubble chimneys and enhanced permeability zones using explosives. Articles in the volume edited by Kruger and Otte (1973) give an overview of several types of stimulation proposals. The two major questions to be answered about the schemes are: will they work in the idealized world of the computer or laboratory model and will they work in the field? Because of the expense of field experiments and the difficulty of obtaining enough data to interpret field experiments, physical and mathematical models are important tools for research.

Several papers were given on hydraulic fractures and the extraction of energy from hot rock using water injected into flat cracks. Abé, Mura and Keer (this volume) discuss the problem of how to solve the equations for the shape of a crack under stress and pressure gradients along the crack. They plan to build up a solution by using dislocation theory. The equations for the coupled fluid-and solid-mechanical problem of crack growth were presented and various approximations introduced that will allow the problem to be solved. Secor and Pollard (1975) have solved for the shape of a crack under the influence of a hydrostatic gradient in the crack and a constant gradient of lithostatic pressure far from the crack by superimposing a number of plane strain elasticity solutions. They apply this solution to discuss at what length the crack becomes unstable as a function of fracture toughness and the difference in gradient between lithostatic stress and hydrostatic pressure.

Pollard (1975) has also investigated the influence of the ground surface on crack shape and stability and the deformation of the ground surface during subsurface cracking. Dundurs (this volume) is modeling fractures by drilling fine holes into a block of epoxy resin, cementing tubes into the holes and supplying mercury under pressure to form hydraulic fractures. One of the experiments was for a crack propagating parallel to an existing pressurized crack at a distance less than the size of the first crack. The second crack turned and joined the first crack. The joint was on the side (not tip) of the first crack and was of a very small size. Further pressurization of the second crack enlarged the first crack but the second crack did not expand. Byerlee, Lockner, and Weeks (1975) have studied hydraulic fractures in sandstone at confining pressures to 1000 bars and differential stresses to 4000 bars. At high injection rates, hydraulic tension fractures were formed, but at low injection rates, shear fractures were formed.

Murphy (this volume) is analyzing the heat transfer to a circular crack whose fracture gap width varies across the crack for the limiting case of no mechanism for porosity generation, so that heat is transferred to the crack only by conduction. The crack is assumed open so that the formula for flow resistance in a thin channel can be used and the conduction problem is solved to provide a kernel for the solution of the fluid flow equation (including buoyancy) and energy equation in the crack. McFarland (1975) has solved several problems for heat transfer and fluid flow including buoyancy in a crack. The flow in circular cracks of elliptical cross section is solved for cases in which the crack is either partly filled with porous material or is open. The crack may contract or retain its shape. Bažant, Nemat-Nasser, and Ohtsubo (this volume) are using finite element methods to solve for the initiation and extension of fractures in hot dry rock and for the circulation of water and heat transfer in the fractured zone. In an example, they compare analytical and numerical solutions for the temperature distribution for water flowing in a stream tube and gaining heat by conduction from the surrounding rocks.

The progress of field studies to develop the extraction of energy using hydraulic fractures has been recently described by Smith, Aamodt, Potter, and Brown (1975). A well drilled to a depth of 2928 m has a bottom-hole temperature of 197°C. Various fracturing experiments have been performed. For example, with a packer set at 2917 m, a single hydraulic fracture was created at a surface pumping pressure of 120 bars with a calculated crack radius of 57 m. A second well recently drilled to a depth of 3060 m has a bottom-hole temperature of 203°C (H. D. Murphy, Written Commun., 1976; Aamodt, 1976). These two wells have been connected by what is thought to be a system of hydraulic fractures.

The second stimulation technique discussed at the workshop was the creation of Permeability by explosions. McKee and Hanson (this volume and 1975) propose that the permeability in the fractured zone beyond the cavity should scale as $1/r^5$ for a spherical blast and $1/r^4$ for a cylindrical blast where r is distance from the shot point., Kruger (this volume) and his colleagues are looking at various aspects of heat and mass transfer. relevant

to stimulated reservoirs. Hunsbedt, Kruger, and London have built a laboratory model of a rubble chimney to study the processes of in-place boiling, moving flash fronts, and two-phase flow. The initial rock loading has a high porosity and permeability so that pressure gradients needed to drive the flow are small. The system is initially filled with liquid water. As it is produced from the top, either no recharge or recharge of cold or hot water is added from the bottom. Plans are underway to scale these experiments to field-size systems. Kuo, Brigham, and Kruger describe another experiment to measure heat and mass transfer rates from a sphere of porous material in a bath of circulating fluid to check if heat transfer rates are enhanced by mass diffusion. Results indicate that mass transfer by molecular diffusion is such a slow process that heat transfer rates are not affected. Stoker, Kruger, and Umana have been looking at the properties of radon as a diagnostic for reservoir studies. Since the emanating power of a rock material for releasing radon is proportional to the exposed surface area, it may be possible to relate radon measurements to the increase in surface area caused by stimulation. Since field data are not available for stimulated reservoirs, measurements are being made on production from natural systems to develop interpretive techniques.

Barnes and Rimstidt (this volume) are studying equilibrium chemistry of silica solubility and kinetics of the dominant reactions. Data obtained will be useful for suggesting ways to manipulate wells in order to prevent scale formation during the flow of hot water in wells and pipes. Sammis (this volume) discusses the modeling of chemical reactions in geothermal reservoirs. Natural fluids in hydrothermal convection systems have long aquifer residence times at high temperatures so that they tend to be in chemical equilibrium with their host rocks. The injection of cold water into a natural or stimulated geothermal reservoir will provide a fluid that is not in equilibrium leading to possibilities of deposition, solution, and redeposition depending upon the initial dissolved-solids content of the fluid and its subsequent temperature history. Summers, Winkler, and Byerlee (1975) have found significant permeability reductions in flowing water through granite at high temperatures, and Charles and Valagna (1975) describe alteration products in the flow of water through monzogranite at high temperature. The results of these and further studies must be integrated into models of fluid injection processes in order to assess potential difficulties.

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SESSION V - MODELLING - James W. Mercer

The goal of this report is to summarize the present status of: geothermal reservoir modelling, and to indicate the future goals of geothermal modelling research. The geothermal modelling effort presented at this workshop is categorized in Fig. 1. The major subdivisions are modelling of natural geothermal systems and modelling of producing geothermal systems. These **two** subdivisions were chosen because, in general, they emphasize two different viewpoints. Modelling of natural geothermal systems is usually done in the vertical cross-section and emphasis is placed on examining free convection in order to gain insight into the natural (pre-exploitation) behavior and formation of geothermal reservoirs. Modelling of producing geothermal systems is usually done in the areal plane. This approach emphasizes simulating exploitation effects in order to reproduce observed field conditions, and hopefully predict future field conditions. Modelling associated with production can be subdivided further as shown in Fig. 1. These divisions will be discussed later.

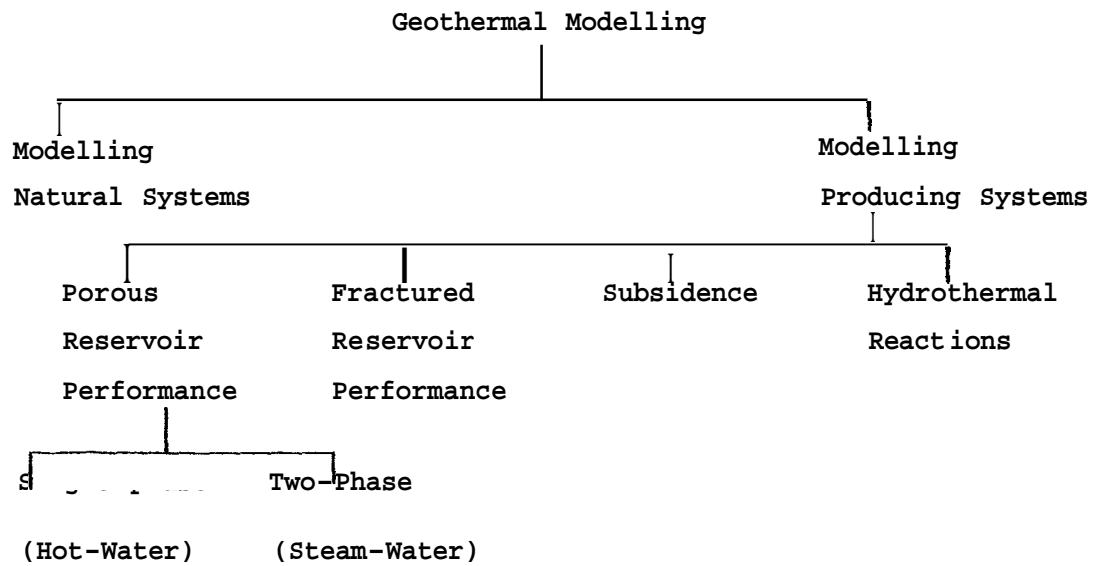


Figure 1.--Status of Geothermal Modelling.

Researchers involved with the modelling of natural geothermal systems include (in the order of their presentations): R. A. Wooding, H. W. Shen, P. Cheng and M. Sorey. Dr. Wooding considers analytical and finite-difference techniques applied to free convection. For reasons of economics, he generally restricts his models to two dimensions. To examine the three-dimensional aspects of the problem, he is collaborating with Dr. Shen, who is using physical modelling (Hele-Shaw cell models) to examine free convection. The physical models developed by Dr. Shen are also being used to verify the numerical models. Dr. Cheng uses finite-difference techniques to examine the free convection associated with volcanic islands, such as the Hawaiian Islands. He has also developed analytical solutions for free convection caused by various types of magmatic intrusions. Dr. Sorey examines the heat and mass transfer associated with various hot spring geometries. He uses a numerical method based on an integrated finite-difference scheme.

It is interesting to note that all of the above models consider single-phase (hot-water) flow. A logical extension of this work would be to include the vapor phase. Such a two-phase, cross-sectional model could aid in testing the various hypotheses concerning vapor-dominated geothermal systems. Although such a model was not presented at this workshop, Dr. T. Lasseter (who was invited to the workshop but could not attend) has considered this problem using a model based on integrated finite-difference techniques.

Researchers involved with the modelling of producing geothermal systems include (in the order of their presentations): C. R. Faust, J. W. Mercer, G. F. Pinder, W. G. Gray, J. W. Pritchett, Z. P. Bafant, S. Nemat-Nasser, H. Ohtsubo, C. G. Sammis, A. Barelli, R. Celati, G. Manetti, G. Neri, S. Bories, and T. Maini. Drs. Faust and Mercer have developed finite-element and finite-difference models for simulating production of geothermal reservoirs. These models can treat single- and two-phase (steam-water) flow, and are capable of simulating the conversion of a compressed-water region to a two-phase region. Drs. Pinder and Gray have concentrated on theoretical equation development and computer code implementation (using finite-element techniques) for multiphase flow (steam-water), subsidence, and flow in fracture media. Dr. Pritchett has developed a finite-difference model for multiphase flow and heat transport. It is proposed that this model be coupled with a consolidation model developed by S. K. Garg in order to simulate subsidence and induced seismic activity. Drs. Bafant, Nemat-Nasser and Ohtsubo use finite-element techniques to examine the formation of fractures (both hydraulically and thermally induced) and the subsequent flow of water in the fractures. Dr. Sammis examines rock-water interactions using finite-difference and experimental techniques. He considers dissolution and precipitation reaction and alteration reaction effects on: (1) reaction heat (chemical energy), (2) changes in permeability and porosity, and (3) changes in the thermodynamic properties of water. Drs. Barelli, Celati, Manetti and Neri examine analytically the pressure history of a partial penetrating well in a hot-water reservoir. Dr. Bories is attempting to determine experimentally the heat transfer coefficients between fluid and rock in a porous system undergoing conversion from single- to two-phase flow. Finally, Dr. Maini uses analytical solutions to examine downhole heat exchange.

Another paper, which does not fit directly into the scheme in Fig. 1, but which encompasses all of the modelling work, was given by R. Atherton on general sensitivity theory. By appropriately modifying a given set of partial differential equations, a sensitivity analysis may be performed on both equation parameters and boundary conditions to determine in which space domains they are important.

Before discussing future goals of modelling, it should be noted that there were other papers which dealt in part with modelling; however, they will be included in the other rapporteurs' reports.

Returning to Fig. 1, it is evident from the papers presented that modelling of porous reservoir performance, both single- and two-phase, is at an application stage. However, modelling of fractured reservoir performance, subsidence and hydrothermal reactions needs further research and development before field applications of this type are possible. Extensions of the models presented include: (1) incorporate a wellbore model and/or near-wellbore model with a reservoir model, (2) include the equation of state for saline water, (3) couple the reservoir model with a management model, (4) perform further sensitivity analysis, and (5) include more rock-water interaction.

One of the most important points made at this workshop is the need for people in modelling to work more closely with people doing laboratory and field work, in order to determine what data are needed and what assumptions are valid. Some of the contributions from laboratory work include: (1) thermal effects on relative and absolute permeability, (2) thermal effects on dispersion, (3) chemical reaction rates, (4) capillary pressure effects, and (5) heat transfer rates between fluid and rock. Contributions from field work include: (1) determination of permeabilities and porosities, (2) reservoir boundaries and thickness, (3) initial pressure and temperature/enthalpy distributions, and (4) reservoir geology.

It is the opinion of this rapporteur that the most important goal for geothermal modelling indicated at this workshop, is the need to make field applications, and if these applications are to be successful, it is essential to have good communication between people doing modelling and people doing well testing and field work.

A PROGRAMMATIC VIEW OF GEOTHERMAL
RESERVOIR ENGINEERING

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I will make my remarks brief in the interest of getting on with the scientific subject of this workshop, which I like to regard as the science of geothermal reservoirs. To be more specific, we are not concerned here with the science or technology of how to find and how to assess the energy potential of these reservoirs (albeit impossible to make a clean separation between the related technologies); but rather our purpose is to focus on the behavior of reservoirs under the stimulus of production and commercial extraction of heat.

At NSF we feel this is a highly opportune moment to convene such a group as this. Many research and development efforts are now underway in this area, and many have reached that point where significant results have been achieved and where new data and new questions are being generated at a rapid pace. (In a moment I will review the recent history of how many of these efforts were initiated through the NSF Geothermal Program.)

Therefore, NSF is pleased to support Stanford University in sponsoring this workshop, and in behalf of the Foundation I want to welcome you here. We have attempted to gather those who are currently active in geothermal reservoir engineering research and who are in the forefront of new knowledge and experience of this rapidly expanding field.

In this objective, I think Dr. Paul Kruger and his colleagues at Stanford have succeeded admirably. The response to workshop invitations, I understand, has been enthusiastic and almost 100% in acceptances. Some request; to attend had to be discouraged, not because the people are not smart enough and not because they lack a legitimate interest in the subject area and findings of the workshop. Rather, attendance had to be constrained to a manageable size so as to enable fruitful and spontaneous exchange of ideas among the active researchers in the field.

Because there is a wide community of interest in these matters, I have asked Stanford to prepare a report summarizing the papers, discussions and findings of these three days. They have agreed to do this, and the report will be made available to all who are interested. Furthermore, I fully expect to see numerous conferences and symposia in the coming year devoted to this and other areas of geothermal science. These meetings, at which many of you will present papers, will provide ample opportunity for the diffusion of new and current knowledge to the whole community of technical and commercial interest.

I want to extend a special welcome to the workshop participants who have come here from other countries. You are not only welcome in our country to participate in this workshop, but we look with anticipation to

strengthen personal and professional relationships with you that will be of mutual benefit in our research efforts in the future.

Now, it may interest you to know how some of the U. S. efforts were started. The first project to be initiated by NSF was right here at Stanford. Paul Kruger in Stanford's Civil Engineering Department had some ideas about tapping steam out of a rubble chimney created by an underground explosion in hot rock, and he wanted to explore the thermal and mass transfer processes to be expected in such a situation and to find ways to extract the heat. Henry Ramey, over in the Petroleum Engineering Department, wanted answers to questions of fundamental behavior of hot water and steam that had arisen in his consulting practice at The Geysers and out of his extensive experience in hot water flooding and other thermal stimulation methods in oil reservoirs. This project was started in July 1972.

Take a look at Figure 1, and see how the funding has progressed at NSF in this important area. Our funding in reservoir engineering research has peaked in FY 1975 as in every area of the NSF Geothermal Program, It is interesting to note in retrospect, that 20% of the \$13.4 million total investment in geothermal energy by NSF over a five-year period has been devoted to reservoir engineering. The investment grew at a somewhat lesser rate in the early period than did the program as a whole, but following the formation of ERDA in FY 1975, It has become a larger fraction of the whole. This increased relative emphasis derives from our policy to focus, not on the engineering applications, not on the utilization technology and the pilot plants and the demonstration plants, and not on the institutional and non-technical barriers to utilization, but rather on the fundamental science problems inhibiting the fullest development of the resource, Clearly, problems concerning reservoir phenomena comprise a significant part of this concern for new fundamental knowledge, and the NSF program is moving in that direction.

Finally, for a word on our currently active projects, each of which will be reported at this workshop, please look at figure 2. Here I have listed the grantee institutions, the research area of each project, the principal investigator, and the cumulative funding through FY 1975. The status of the research represented on this list will unfold in the three days ahead of us.

It is going to be a very stimulating three days, as not only the NSF research is described but also that of the U. S. Geological Survey, in the ERDA laboratories, in the field and in laboratories of private U. S. companies, and in foreign countries with active geothermal programs and who are represented here today.

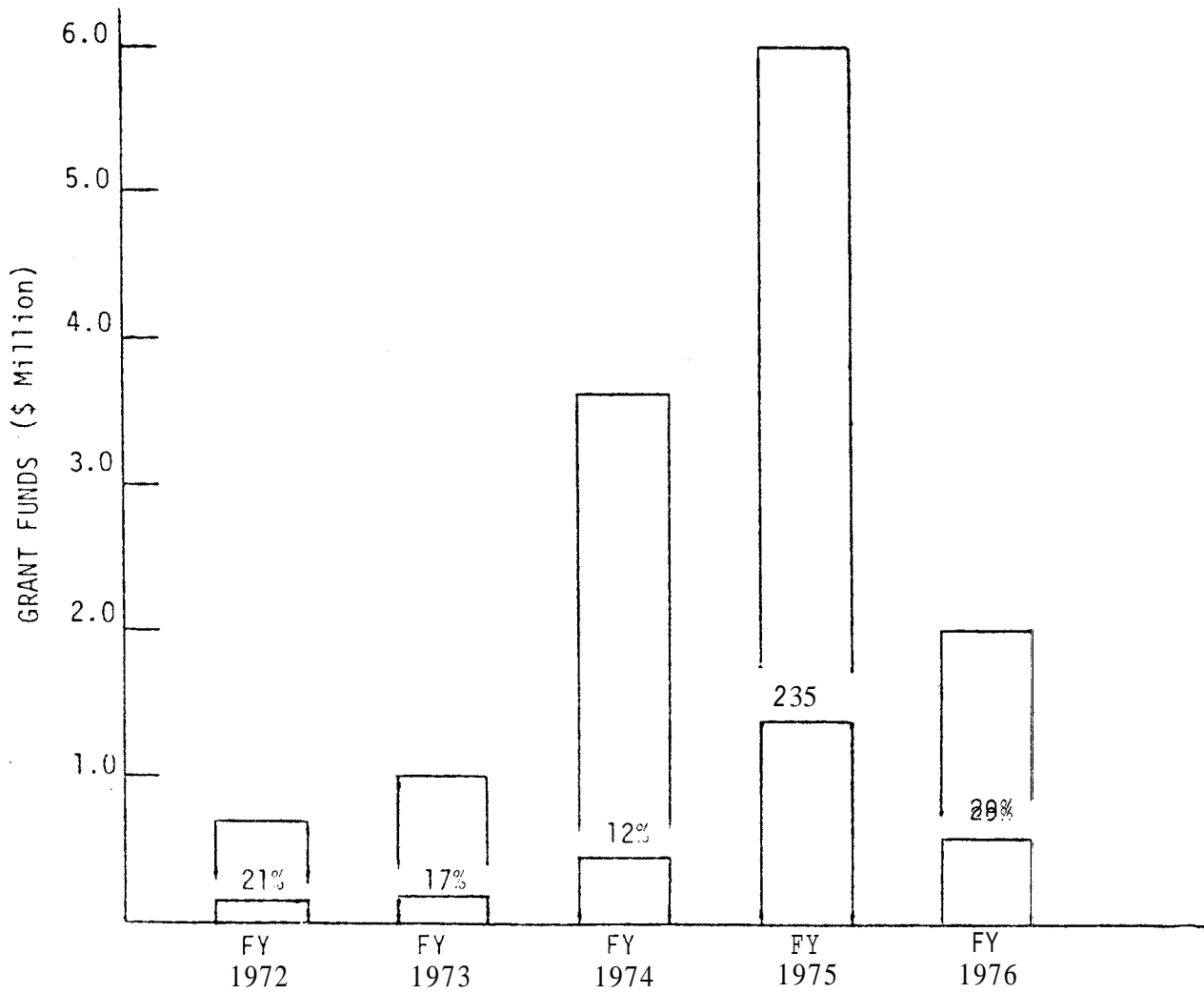


Figure 1. Reservoir Engineering Support in the Geothermal Energy Program of The National Science Foundation.

National Science Foundation
 GEOTHERMAL ENERGY PROGRAM
 RESERVOIR ENGINEERING PROJECTS

Institution	Research	Principal Investigator(s)	Funding thru FY75
Stanford U.	laboratory experiments in heat and mass transfer	Henry Ramey, Jr. Paul Kruger	\$ 586,700
Penn State U.	laboratory experiments in reservoir chemistry	Hugh Barnes, Wayne Burnham	402,000
Princeton U.	numerical modeling of Wairakei field by finite element method	George Pinder	249,500
Colorado U.	numerical modeling problems by finite difference methods	David Kassoy	248,300
Systems Science	numerical modeling of Salton Sea field by finite difference methods	John Pritchett	378,000
U. of Hawaii*	numerical modeling of coastal aquifer problem	Ping Cheng	61,100
Northwestern U.	rock mechanics problems in stimulation of geothermal reservoirs	Hans Weertman	213,900

*

Transferred to ERDA under Hawaii Geothermal Project

Figure 2

THE BIRTH OF GEOTHERMAL RESERVOIR ENGINEERING

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The term "reservoir engineering" arose within the field of study of the development of gas and oil reservoirs. One definition of reservoir engineering is the application of scientific principles to the drainage problems arising during development and production of oil and gas reservoirs. Although many important physical laws concerning reservoir mechanics were established during the first half of this century, reservoir engineering has flourished mainly since the end of World War II. The combination of the recognition of increasing energy requirements in a rapidly industrializing world and the release of trained manpower following World War II abetted the development of the field of reservoir engineering. In the 1940's and 1950's oil recovery processes such as underground combustion of oil and oil recovery by steam and hot water injection received great attention. The modern development of geothermal reservoirs also began to accelerate about that time. The pioneering geothermal development in Larderello, Italy, began the massive job of rebuilding the devastation of World War II. New Zealand began the important development of geothermal power in the Wairakei steam field, and the Magma-Thermal Power Company development of the Geysers in California, USA, followed thereafter.

Nevertheless, it was not until the early 1960's that petroleum reservoir engineering principles were first applied to geothermal reservoir problems. It appears that the first such study was conducted by Whiting and Ramey in the mid 1960's (Whiting and Ramey, 1969). As a result of this work, Cady began an experimental study of the importance of capillary pressure on boiling within porous media in 1967 (Cady, 1969), a line of study which continues to this date. A second reservoir engineering study of a geothermal field was presented by Ramey in 1968 concerning the Geysers Geothermal Field in California.

Although reservoir engineering principles were widely known for 20 years prior to application to geothermal reservoirs, the birth of geothermal reservoir engineering appears to date to the early 1960's. This is not to say that geothermal reservoirs were not subject to scientific study closely related to modern reservoir engineering. It appears that the types of investigation were more closely aligned to the fields of geology, geophysics, hydrology, and geochemistry.

The reason for this situation appears to lie in a misunderstanding concerning petroleum reservoirs. In one state publication concerning geothermal resources, it was remarked that because petroleum reservoirs were always closed pools and geothermal systems were always active hydrothermal systems, there was nothing applicable within the field of petroleum reservoir engineering. The conclusion that geothermal systems were large hydrothermal systems subject to natural "recharge" also had an effect. It

had been theorized that geothermal systems could be self-regenerating if developed properly. It was only necessary to discover the natural recharge rate (both heat and fluid) and produce at that rate to have a steady-state system which would never deplete. It now appears that few if any natural systems can recharge at the phenomenal rates required for electric power generation.

The remark that petroleum reservoirs were always closed pools is incorrect as well. The first study of oil reservoir performance subject to water recharge (influx) was published in 1930. The word "reservoir" is now used in the same sense as a "thermodynamic system." It is possible to have transport into and out of the system, of course. Let us then turn to geothermal reservoir engineering as a new field of study.

Although many of the principles of reservoir physics involved in non-isothermal oil production by fluid injection (oil production by underground combustion and steam injection) are reasonably well understood, it is not surprising that some problems appear to remain for geothermal reservoir physics. For this reason, Cady (1969) studied geothermal system behavior with the physical model prior to 1969. A speculation that capillary pressure might reduce the vapor pressure of liquid water to a substantial degree was responsible for the Cady study. Although vapor pressure suppression was not noticed in Cady's work with an unconsolidated sand core, he did make the surprising observation that an isothermal dry steam zone could develop within a few inches above a two-phase boiling zone which followed the vapor pressure curve for water as pressure declined. A search for capillary pressure effects upon boiling continues at Stanford.

Unfortunately, it is difficult to scale all important physical parameters between the field and the laboratory. Many important physical phenomena have been discovered by thorough analysis of field performance data. However, field data for geothermal systems are not readily available. In reservoir engineering it appears that there is no hope of ever physically examining the reservoir directly. It is not likely that we shall mine or exhume many reservoirs. Thus, the responsibility of the reservoir engineer usually involves a two-step process: (1) to make and interpret indirect measurements of the quantitative characteristics of the reservoir, and (2) to employ this information and basic physical principles to forecast the behavior of the reservoir under any potentially useful production scheme. The second step assumes that all basic physical principles are known. Herein lies the need for much field and laboratory experimental work. Even in the much older field of petroleum reservoir engineering, it is clear that much remains to be discovered concerning basic physical principles. See recent discussions of reservoir engineering by Wyllie (1962) and Ramey (1971).

Ramey pointed out that such important information as can be determined by direct measurement on reservoir samples (cores) often leaves much to be desired. The difficulty with core analysis information lies in relating it to the reservoir. Indeed, as Wyllie has pointed out, why should we assume that the reservoir is like the minuscule volume of rock samples taken out of the reservoir and discarded? Many important computations

and decisions are reached, nevertheless, upon the basis of quantitative information derived from core samples.

By now, interpretation of information derived from cores should be well established and standardized. It is not! There is no consensus of proper methods of handling core data. Wyllie made an eloquent plea that the approach to reservoir engineering be holistic (that the determinations be made in wholes, not in parts--for example, that "what matters is the rock unit and not samples of arbitrary size that may have been taken from it"). He cited pressure buildup and drawdown testing. Determining the characteristics of the reservoir by in-situ measurements using wells as the input and output flow faces of the reservoir "core" makes a great deal of sense. Reservoir simulation by digital computer is another highly popular technique that embodies the holistic approach. We attempt to generate a detailed description of a reservoir to match all known performance data. If the matching is successful, we assume that a reasonably accurate model of the actual reservoir system is available and employ it to forecast behavior under various operational schemes. To restate this situation, performance matching consists of developing an n-dimensional mathematical reservoir model that responds to model fluid production as the prototype responds to actual fluid production. The "response" involved usually means pressure response. In the case of geothermal systems, we generalize production to include both fluid and energy, and response to include pressure, temperature, enthalpy, quality, and composition. The birth of geothermal reservoir engineering is accomplished, and we await the development of the child.

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SUMMARY DESCRIPTION OF RESEARCH ACTIVITIES

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The basic goal of the University of Colorado Geothermal Research Program has been to assess, characterize and model the myriad of physical processes occurring in the geothermal environment. While developing an understanding of the fundamental nature of these phenomena we can construct a comprehensive model of the structure of a given geothermal system. Such a result should prove useful in the interpretation of surface geophysical measurements and for the general development of a geothermal field. Our studies spanning the range from heat and mass transfer process in hydrothermal convection anomalies to the possible appearance of dilatancy due to large rates of liquid withdrawal, are carried out by a diverse group of engineers, geophysicists, geologists, seismologists and experts in computation. Much of the effort has been carried out with the cooperation of the geothermal group at Systems, Science and Software, La Jolla, California.

The following summary of activities provides an extremely brief description of the ongoing research programs, their purpose and when appropriate, the results obtained.

Physical Characterization

Black⁽¹⁾ has carried out a subsurface study of the Mesa anomaly in the Imperial Valley. His studies have shown that:

- (1) There is a cap of low vertical permeability composed of a large fraction of clay-like material.
- (2) Below the cap are relatively compacted, sandy strata with significant permeability.
- (3) Fracturing in deeper rock layers, presumably associated with seismic activity increases vertical permeability.
- (4) Intersecting fault zones near two wells have produced a chimney of particularly high vertical permeability. Substantial upwelling of hot water from depth occurs here as well as along the linear fault zone to the southeast.
- (5) The rising hot water spreads laterally, mostly to the southeast as the fault zone intersects relatively permeable horizontal aquifers.
- (6) Reduced salinity of water at depth compared to that in upper levels (0-800m) implies greater circulation and less evaporites in the deeper zone.

Rinehart (2) has considered the presence of faulting in geothermal areas. He has concluded that:

- (A) Almost all productive geothermal areas are associated with faulting. Many of these are patterns of ring fractures associated with calderas while others are linear features associated with rift zones.
- (B) Fault zones act as conduits for the flow of heated fluid from depth. They can affect the supply of surface water to the system at depth.

Mechanical Models

Rinehart (3) has suggested a possible physical mechanism for the observed cyclic variation in flow rates and water table level associated with saturated porous media subjected to temporal alterations in in-situ stress due to tectonic and tidal forces. Making reasonable assumptions, he argues that a solid block supported by a saturated porous material could move as much as several centimeters due to periodic mechanical loading. This implies that the effective permeability of fracture reservoirs can be altered substantially.

Archambeau (a) is currently developing nonlinear models of subsidence due to irreversible pore collapse. Included is the possibility of structural rock failure (induced seismicity) due to dilatancy resulting from high levels of effective stress as pore pressure is reduced.

Heat and Mass Transfer

Kasoy and Zebib (4) examined the effect of a realistic viscosity variation on the onset of convection in a horizontal porous slab. Critical Rayleigh numbers are drastically reduced w/r to the constant property calculation. The roll patterns display relatively high velocities and large temperature gradients at depth unlike the symmetric classical profiles.

Kasoy (5) has considered convective flow in a narrow vertical saturated porous slot as a model of mass transfer in a fault zone. The mass flow rates, resulting partly from convection due to pressure head and partly from natural convection, are of the magnitude 10^6 kg/day over an area 0.5 km^2 when the permeability is 10^{-9} cm^2 .

Garg et al. (6) have computed the flow pattern and temperature variation in a horizontal aquifer when fluid is introduced from an intersecting vertical fault zone in which there is hot fluid rising from depth. The solution shows the development of a confined natural convection cell in the aquifer. Hence, in the model considered lateral spillage from the fault zone does not result in simple through flow in the aquifer.

Kasoy and Zebib^(b) have extended their work to three-dimensional containers more representative of geothermal areas in highly fractured rock of volcanic origin. The results also portray linear convection patterns in narrow vertical fault zones, and may be used to explain the presence of periodically spaced hot springs along linear fault zones. Kasoy^(c) has shown that natural convection instabilities can enhance the vertical fault zone flow described above.

Kasoy^(d) has extended his analysis to include lateral spillage into intersecting horizontal aquifers. The pressure and temperature distributions are reminiscent of those found in the Mesa geothermal anomaly. Linear instability at critical a Rayleigh number leads to superimposed closed rolls. These might be used to explain the pair of hot spots at the Mesa anomaly.

Nayfeh⁽⁷⁾ ~~et al.~~ have examined two-temperature models of flow in porous media. They conclude that for most geothermal applications the fluid and solid are in local thermal equilibrium.

There has been a major effort to develop useful describing equations for thermally active deformable porous media containing two phase fluids with concentration gradients. This work is summarized in Refs. 6 and 8.

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*CUMER refers to Mechanical Engineering Report, University of Colorado.

(a) - (d) - Ongoing research activities.

HEAT AND FLUID FLOW EXPERIMENTS TO MEASURE GEOTHERMAL RESERVOIR PHYSICAL PARAMETERS

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BENCH-SCALE MODELS

The test objectives and apparatus involved in the bench-scale models were presented in Progress Report No. 1 (Ref. 1). In brief, these experiments were designed to test fundamental concepts for nonisothermal boiling two-phase flow through porous media. This work is aimed at the entire reservoir, while the chimney model deals most directly with the wellbore and near-well reservoir conditions. The combination should be broadly useful in the new field of geothermal reservoir engineering.

The term "geothermal reservoir engineering" is an adaptation of "petroleum reservoir engineering," the branch of engineering which deals with assessment, and planning, of optimum development of petroleum reservoirs. Fortunately, there is much that is useful for geothermal engineering in the literature of oil recovery. Oil recovery by steam injection (Ref. 2) and underground combustion (Ref. 3) present some of the important features of nonisothermal two phase flow which appear pertinent to geothermal reservoirs. In addition, there is a considerable body of useful data on the properties of rocks and fluids as a function of temperature and pressure. Many of these data are summarized in Reference 4. Prior to this work there was only one specific study of the flow of single-component (water) two-phase (thus nonisothermal) flow in porous media (Ref. 5). In particular, there was no information on the important phenomena involved when normally immobile liquid saturations (practical irreducible water saturation) vaporize with pressure reduction.

The first bench-scale models use steady-state flow experiments involving linear flow (in the axial direction) through cylindrical cores.

The Linear Flow Model

The linear flow model is described in Progress Report No. 1 (Ref. 1) and in Reference 6. Equipment was constructed to perform linear flow experiments through cylindrical consolidated cores. Both natural (Berea) and synthetic cement consolidated sand cores were used. A schematic diagram of the completed apparatus is shown in Fig. 1. Fondu calcium aluminate cement, silica sand of about 100 Tyler mesh size, and water were used as the materials to make the synthetic cores. The mixture was poured into a mold formed with a plastic tubing in which a glass tubing for a liquid content probe and a thermocouple tubing were held in place. The liquid saturation probe was originally developed by Baker (Ref. 7) in connection with a study of oil recovery by injection of steam. The instrument uses the difference in dielectric constant between the liquid water and steam present in the pore space.

It was decided to run a series of basic single-phase experiments prior to performing the boiling two-phase, nonisothermal flow experiments. These included: (1) measurement of absolute permeability to gas and liquid water at a range of temperatures, (2) injection of hot water into a system containing water at a lower temperature, (3) cold water injection into a system containing hot water initially, and (4) injection of steam into a system containing liquid water at a lower temperature. Detailed results are presented in Ref. 6.

As an example, Figure 2 presents temperature versus distance along the core for injection of hot water into a core initially at room temperature. Much useful information can be extracted from data such as are shown in Fig. 2. Basic information on single-phase nonisothermal flow, effective thermal conductivities in the direction of flow, and heat loss radially from the core may be found. In regard to radial heat loss, two determinations can be of interest: (1) the thermal efficiency of the injection, and (2) the overall heat transfer coefficient for the core within the sleeve to the surroundings. Both types of evaluation have already been made successfully. An example of the heating transients that occur when hot fluid is injected into a cold porous medium can be seen in Figure 3. The computed results compare rather well with the experimental results; however, improved mathematical modeling can improve the computed match of these data.

An additional preliminary series of experiments was run to determine the in-place boiling characteristics of a flowing system. Figure 4 shows a particularly interesting experiment wherein the original fluid in place was hot water at high pressure. Notice that cooler water was injected at one end, causing a temperature transient with time, while at the other end, a two-phase boiling zone was set up which remained at a fixed temperature with time. Further analysis of these data and other similar data will be forthcoming during this next year.

Permeability Measurements

Recent work on the effect of temperature on relative permeability suggested that absolute permeability was also a temperature dependent property of rocks. Equipment was designed to measure absolute permeability under conditions of elevated temperature and overburden pressure (Ref. 8). Several fluids were used to make these measurements, namely, distilled water, white mineral oil, nitrogen, and helium.

Several conclusions can be drawn from the results. First, the temperature effect on permeability depends on the nature of the saturating fluid. In the case of water-saturated cores, permeability decreased with increasing temperature for all the samples studied. Over a temperature span of 70-325°F, permeability reductions of up to 65% were observed.

For oil-saturated samples, a slight increase in permeability was observed with increasing temperature in the low temperature range, followed by a decrease. However, this thermal sensitivity barely exceeded the range of experimental error.

On the other hand, absolute permeability to gas was found to be independent of temperature. Slip phenomena are affected by temperature, and a linear relationship between the Klinkenberg slip factor and temperature was found and explained by analysis of theory. Also, inertial ("turbulence") factors were determined and found to be independent of temperature.

One of the objectives of this work had been to simultaneously measure the effect of thermal stresses and mechanical stresses on permeability. It was found that regardless of the nature of the saturating fluid, the level of confining pressure affected permeability in the same manner, that is, permeability decreased with increasing confining pressure. For the thermally sensitive, water-saturated cores, increasing the confining pressure had the additional effect of intensifying the temperature dependence. This pressure-temperature interaction is shown to a marked degree in Figure 5.

In the light of the results obtained, it appears that the temperature effect was not caused by changes in the physical properties of the fluids, such as viscosity or density, because fluids with such a large viscosity and density contrast as oil and gas essentially yielded the same results; nor was the temperature effect caused by thermally induced mechanical stresses acting alone, as no significant permeability changes were found for oil or gas flow. Instead, the unique results obtained for water flow suggest that a combination of rock-fluid interaction, thermal stresses and mechanical stresses was responsible for the permeability reductions observed, the dominant factor being the surface effect.

Geothermal Reservoir Physical Model

Whiting and Ramey (Ref. 9) presented the application of energy and material balances to geothermal reservoirs. Although applied to a field case with success, later applications indicated a need for modification (see Refs. 10, 11, and 12). The need for actual data to test conceptual models has been apparent for some time (Ref. 13). Previous works concerned unconsolidated sand models, although a study by Strobel did include a consolidated sand. Strobel's study concerned cyclic production and reheating of a single consolidated sandstone geothermal reservoir model. This work has been repeated with both natural and synthetic sandstone cores with more complete instrumentation. These data are not only important for the determination of proper material and energy balance procedures for gravity-dominated geothermal systems, but they are also of great help in determining the vapor pressure changes that occur as the in-place liquid evaporates and the liquid interfaces become highly curved. An example of vapor pressure lowering can be seen in Figure 6 (Ref. 14).

MATHEMATICAL MODEL

Advances have been made in the modeling of geothermal fluids production in four main directions. The first direction is a general view of the many complex thermal, fluid dynamic, and other physical processes. The second is the formulation of a mathematical description of a simplified system to obtain a solution describing the behavior of this system. The third is matching the bench-scale experimental results to simulate the boiling flow of steam and water at elevated temperatures. Figure 7 presents the results of one simulation of a bench-scale geothermal reservoir model experiment. Figure 7a presents the computed pressure history, while Fig. 7b presents the computed liquid content of the system. Although not shown, the temperature history of the system was also computed. Development of a more sophisticated model continues.

The fourth major direction of mathematical development is aimed toward a graphical-analytical approach to solution of the heat-mass flow problem. The method of characteristics is a well-known solution technique which appears to be applicable to this problem. An analogy may be drawn between this and the classic problem of water or gas displacing oil in petroleum reservoir engineering (i.e., the Buckley Leverett equations and the Welge equations). Solutions to these displacements are simple graphical constructions. It appears likely that similar techniques may be used in the fluid-heat flow system, and work will be continuing on this concept during the coming year.

CONCLUDING REMARKS

During 1975 the main components of the projects in the Stanford Geothermal Program were completed and initial runs performed successfully. Augmentation of system instrumentation, completion of improvements in design, and collection of experimental data are well under way. It is encouraging that many of the experimental results have been found amenable to theoretical analysis, thus the systems behave reproducibly and logically.

As in any research program, ideas for new experimental techniques and new methods of data evaluation have developed as the program proceeds. These new ideas also are being actively pursued.

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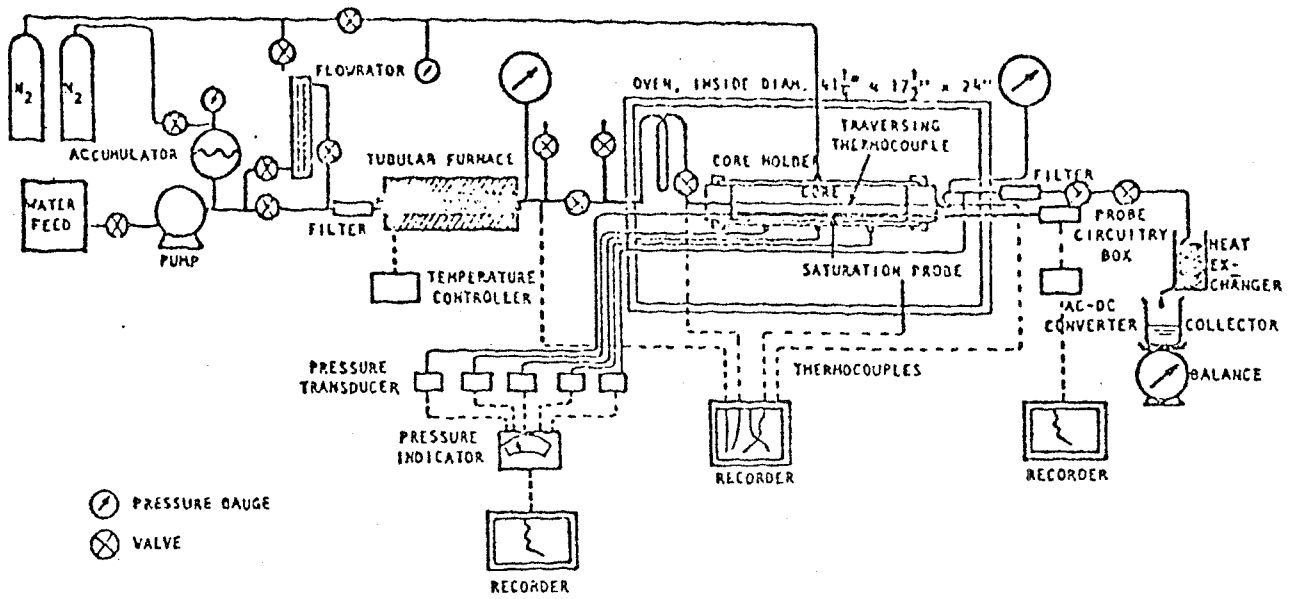


Fig. 1. Schematic diagram of the linear flow model apparatus

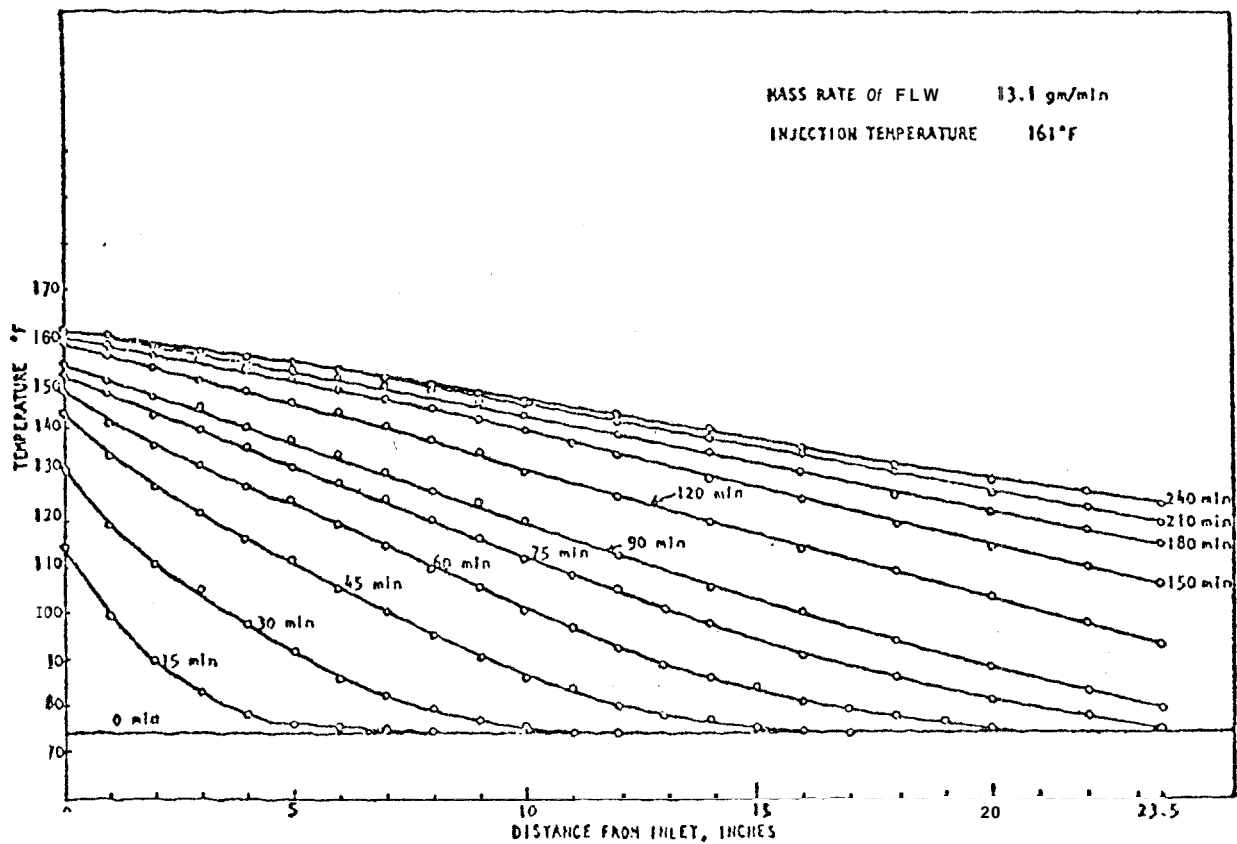


Fig. 2. Temperature vs distance for hot water injection

RUN No. HWI-B-1

---○--- EXPERIMENTAL RESULT

— COMPUTED RESULT

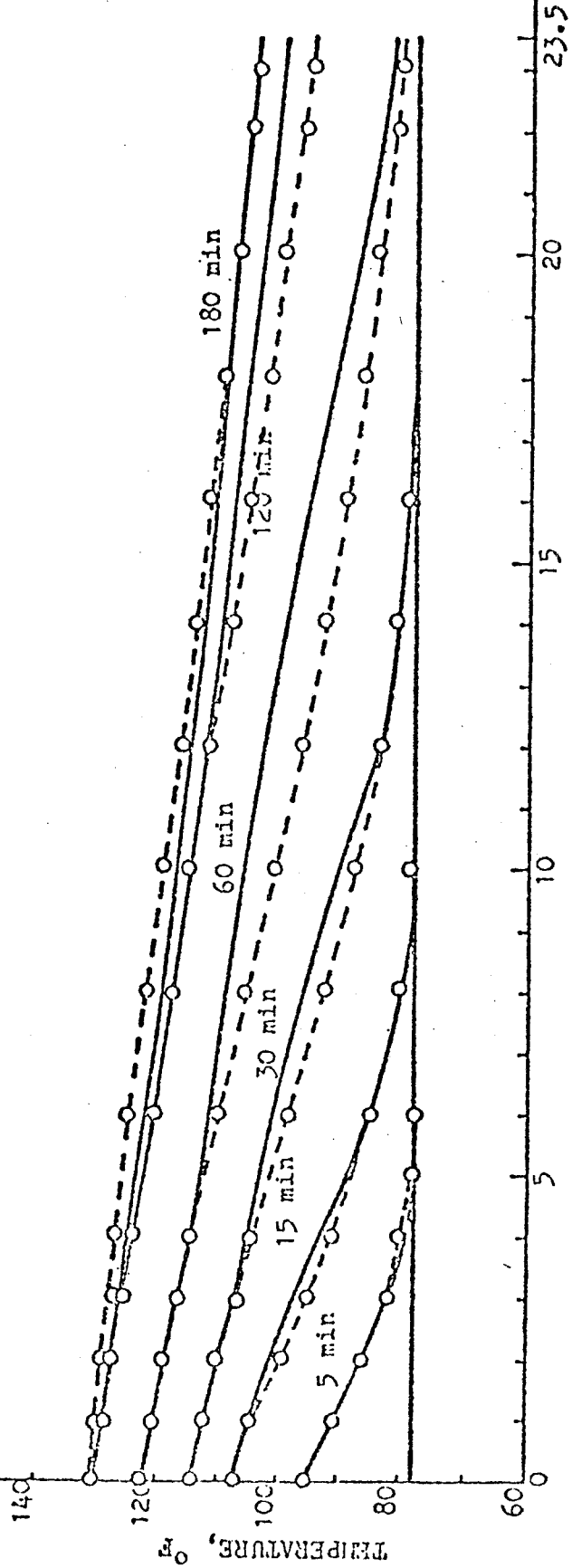


FIGURE 3. COMPARISON OF THEORETICAL AND EXPERIMENTAL TEMPERATURE DISTRIBUTIONS FOR HOT WATER INJECTION, BEREA SANDSTONE

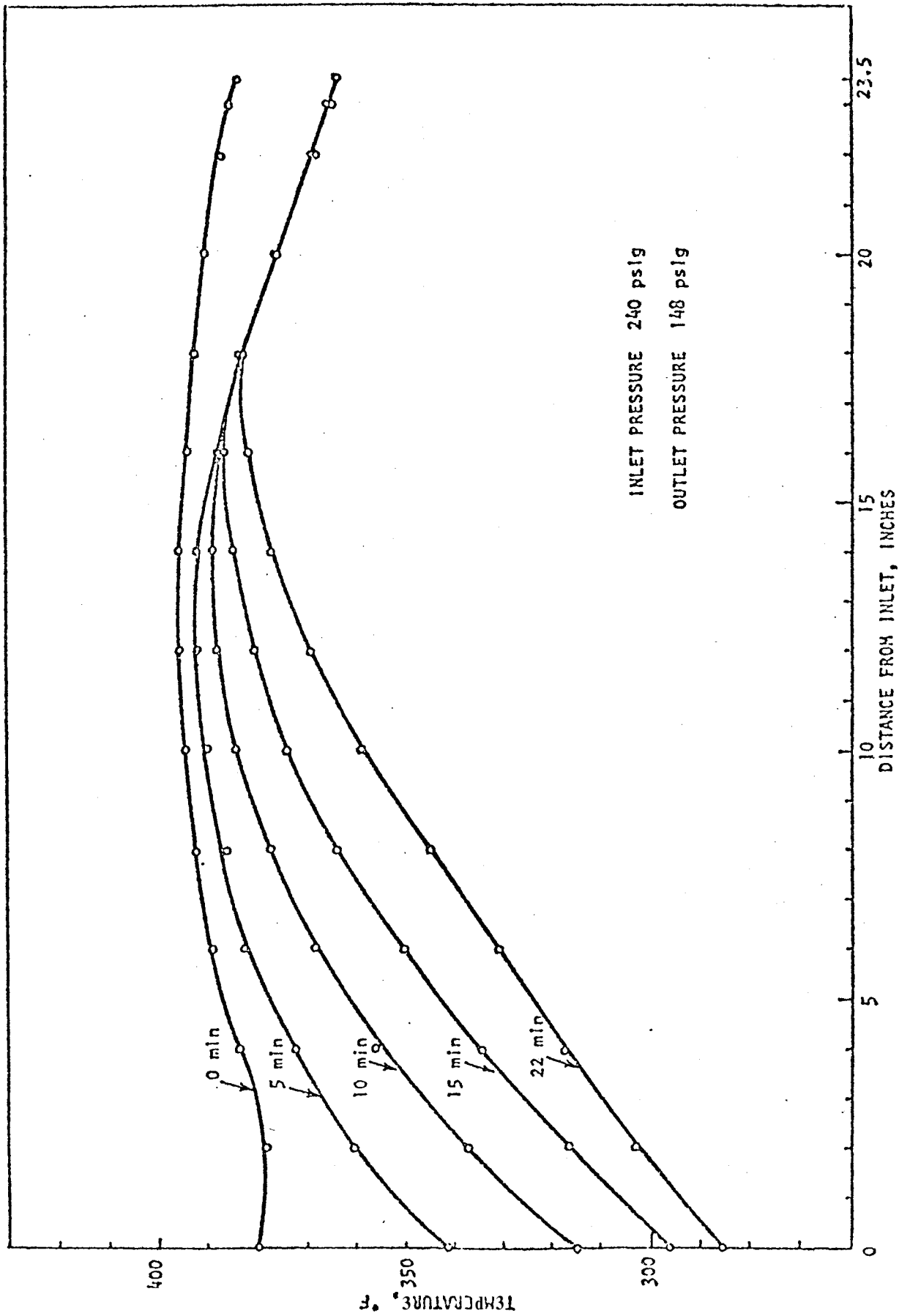


FIGURE 4. TEMPERATURE VS. DISTANCE FOR TWO-PHASE FLOW, SYNTHETIC SANDSTONE.

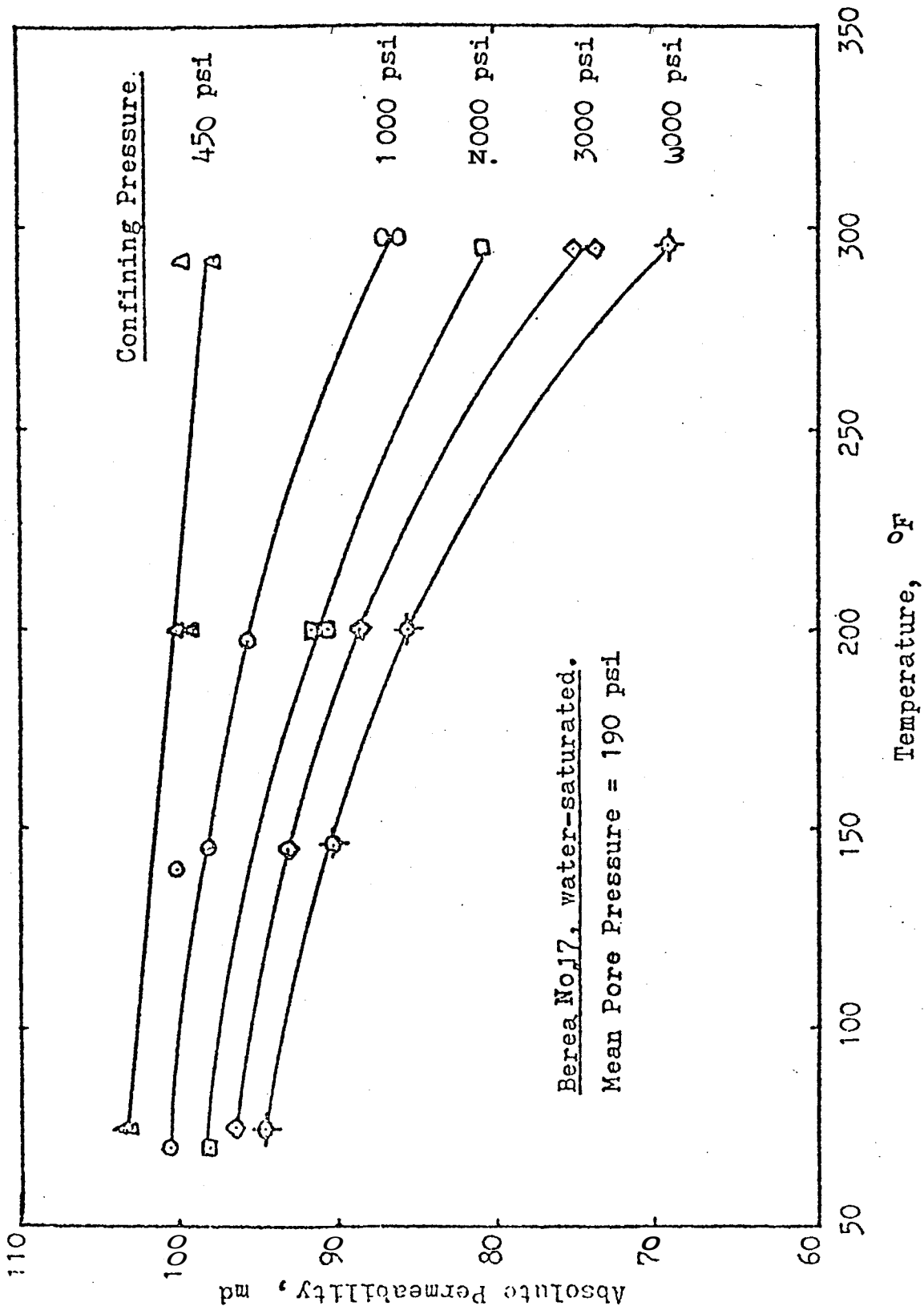
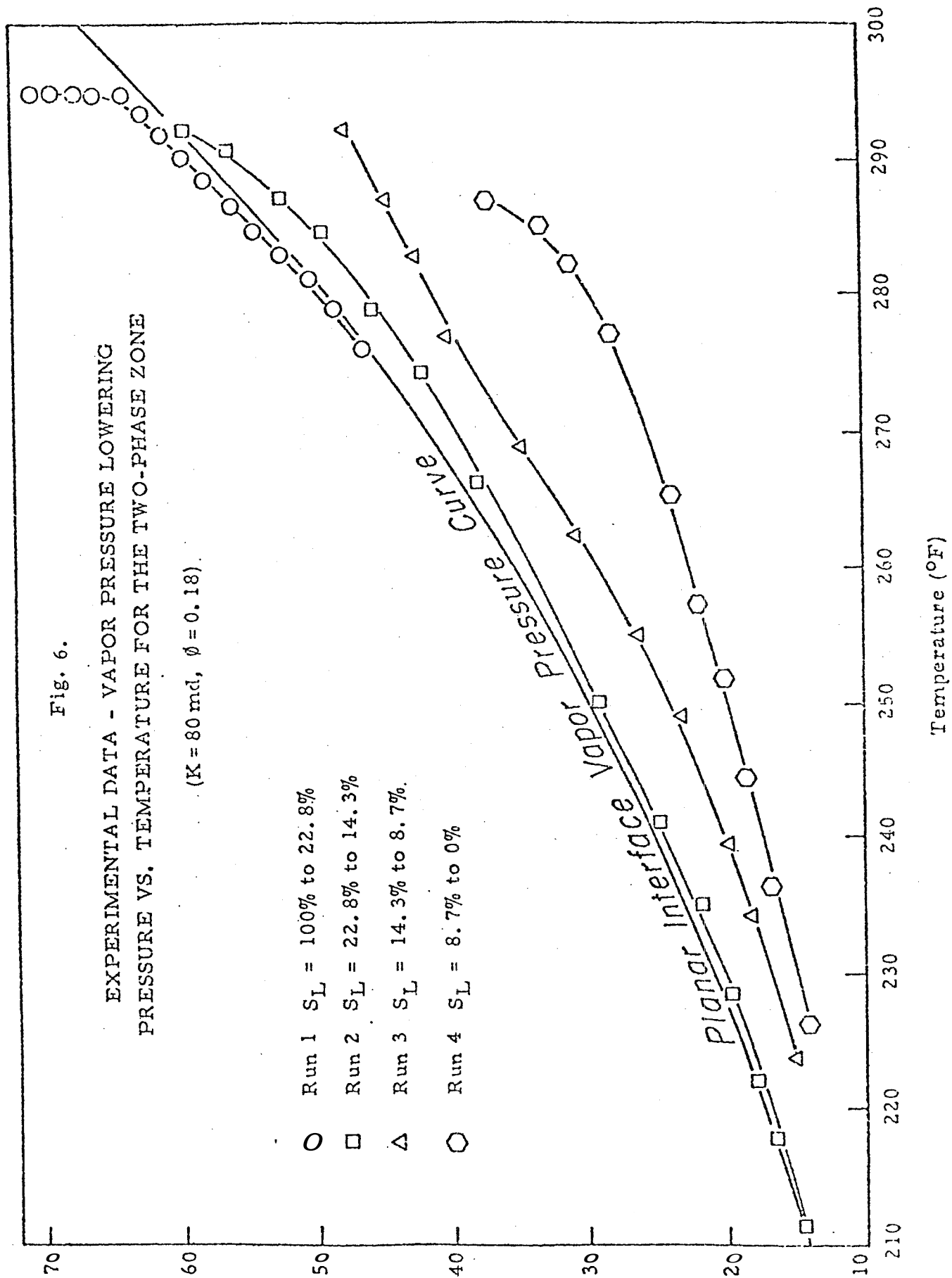


Figure 3 Permeability Change with Temperature and Confining Pressure.



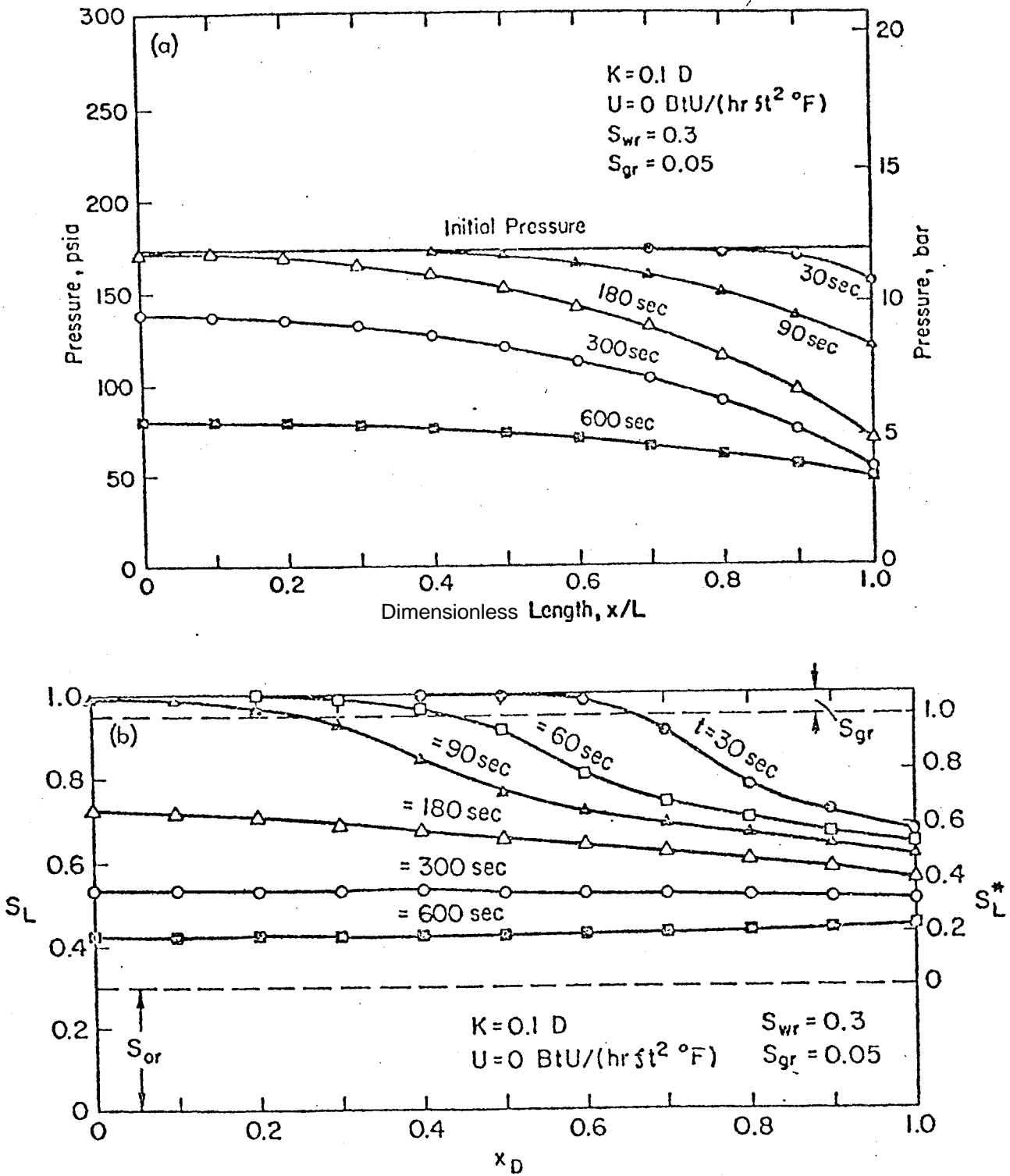


Fig. 7, (a) Simulation No. 1 of pressure history, (b) simulation No. 1 of saturation history

AN ATTEMPT TO CORRELATE Kh DISTRIBUTION WITH GEOLOGICAL
STRUCTURE OF LARDERELLO GEOTHERMAL FIELD

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Steam production in Larderello field is obtained from fractured rocks having a very low matrix permeability.

Fractured zones are irregularly distributed and their location is one of the main objectives of present geophysical research and one of the principal problems in field exploitation. This problem has also been approached from a geological point of view in an attempt at finding the relationship between secondary permeability and the lithological and structural characteristics of the reservoir formations.

The first results, obtained by Cataldi ~~et al.~~ (1963), found a high ratio of productive/unproductive wells along the axes of the positive structures.

The present study of the Kh distribution in Larderello fields should permit a more detailed analysis of the different geological factors affecting the productive capacity of the reservoir formations.

Kh Distribution

Kh values were obtained for about 50 wells in Larderello area from pressure build-up analysis, using both the classical Horner method and different type-curve matches. Other methods of analysis for fractured media were also considered.

Almost the same number of values were obtained from the analysis of back-pressure curves. A comparison, possible for several wells, of the Kh values obtained from both methods shows that a good agreement exists only if skin-effect is taken into account. If not, the values given by the back-pressure curves are almost systematically higher (as much as 50 to 100%) than those given by the build-up curves.

The wells considered have a satisfactory distribution over the entire field area. In some marginal zones the majority of them are completely unproductive, due to lack of permeability, so that no tests were performed on them.

In other zones with unproductive wells, despite the fact that these have crossed permeable horizons, only a few data from injection tests are available.

The Kh distribution in these zones is not well defined.

The wells with similar transmissivity values are usually grouped together, with a few rare exceptions.

The contour lines in Figure 1 refer to Kh values taken in a geometrical progression as the curves are better defined in this way. The line corresponding to 1 Darcy-metre is not reported due to the lack of data in the marginal zones,

Comparison with Geological Structures

Figure 2 shows the elevation of the top of the formations forming the potential reservoir.

This map was obtained by geometrical interpolation between the elevations observed in the wells: the fault planes are not indicated.

From Figures 1 and 2 there is enough evidence of a correspondence between the high transmissivity zones and the structural highs, thus proving that tectonics plays a very important part in determining secondary permeability in the reservoir formations.

Other factors contribute to this permeability and they are thought to explain the observed anomalies in transmissivity distribution where this is not attributable to the structures.

Among these, lithology, lithostatic and fluid pressure must be taken into account.

Other important factors, such as dissolution and deposition, are the object of geochemical studies.

Discussion

The sequence of terrains in the Larderello zone are commonly known to be, as follows, from top to bottom:

- a) the shaley cap rock formation;
- b) sandstones that are irregularly distributed in the productive areas and usually separated from the lower formations by an impermeable layer of shales;
- c) Competent, stratified and massive limestones distributed irregularly over the productive area;
- d) alternations of dolomites and anhydrites, not always present in the productive area, quite plastic if taken as a whole;

- e) a series of terrains comprising incompetent slate layers and competent quartzites.

The potential reservoir is considered to be made up of c) , d) and e).

The contact between the different formations is generally tectonic and caused by mainly horizontal-type movements.

The contact zone, therefore, (and especially that between the cap rock formation and all the underlying ones) are characterized by intensive fracturing and have a high secondary permeability.

Furthermore, the whole region was subjected to compressive stress during the last phases of orogenesis thus resulting in the folding of the layers forming the potential reservoir. The permeability in the crest zone of the anticline structures may be said to have increased due to tension cracks and fissures. Cavities may also have formed along the crests due to the differential movements of the beds.

These facts may have given the greatest contribution to fracturing the upper parts of the positive structures.

Future Developments

This research will now be aimed at studying the distribution of plastic and competent layers inside formation e), the existence of overthrusts within the formations described and especially in e), and the role of the direct faults formed after folding and thrust movements. A study will also be made of fluid and lithostatic pressure.

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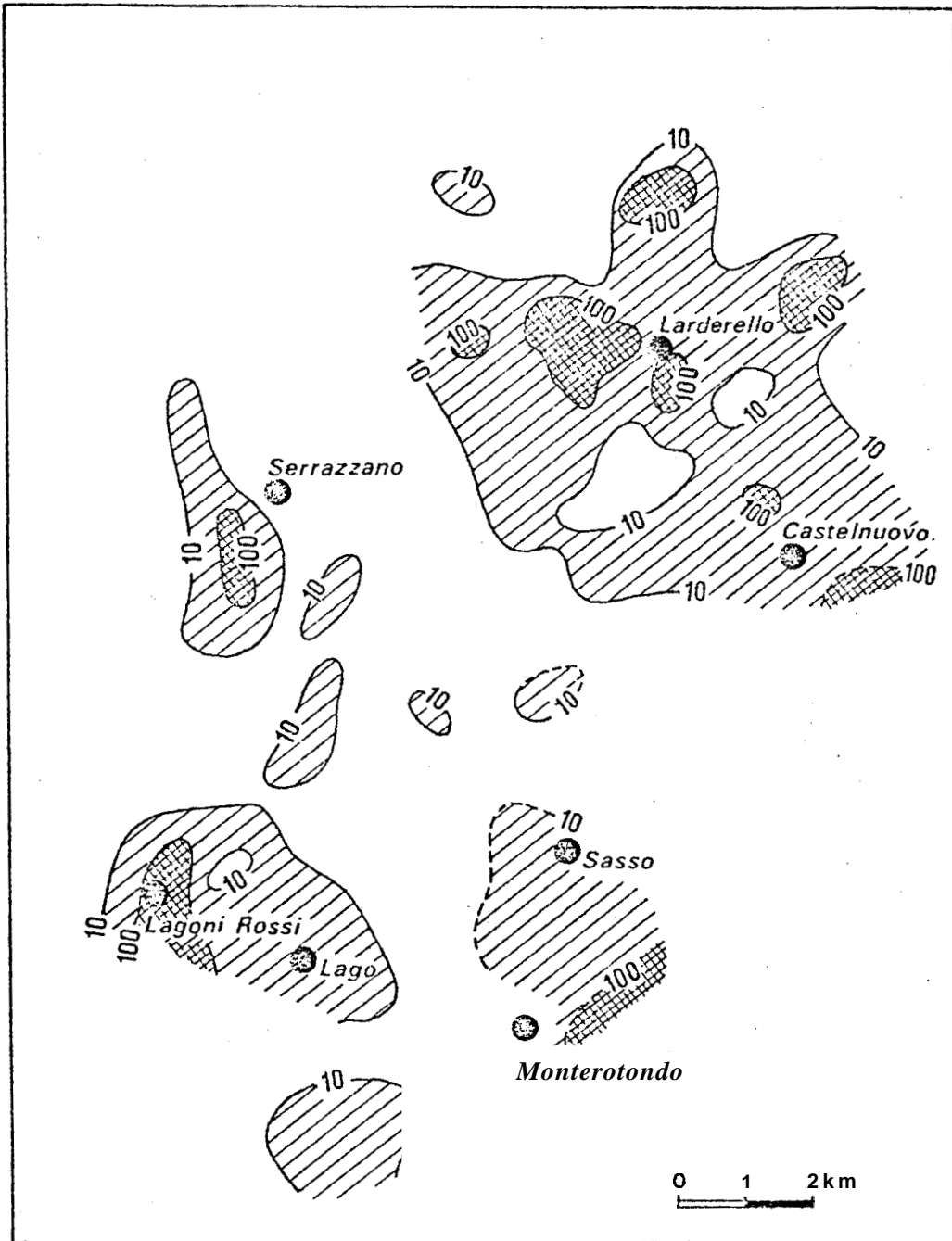


Figure 1 : kh distribution in Larderello field in Darcy-metres.

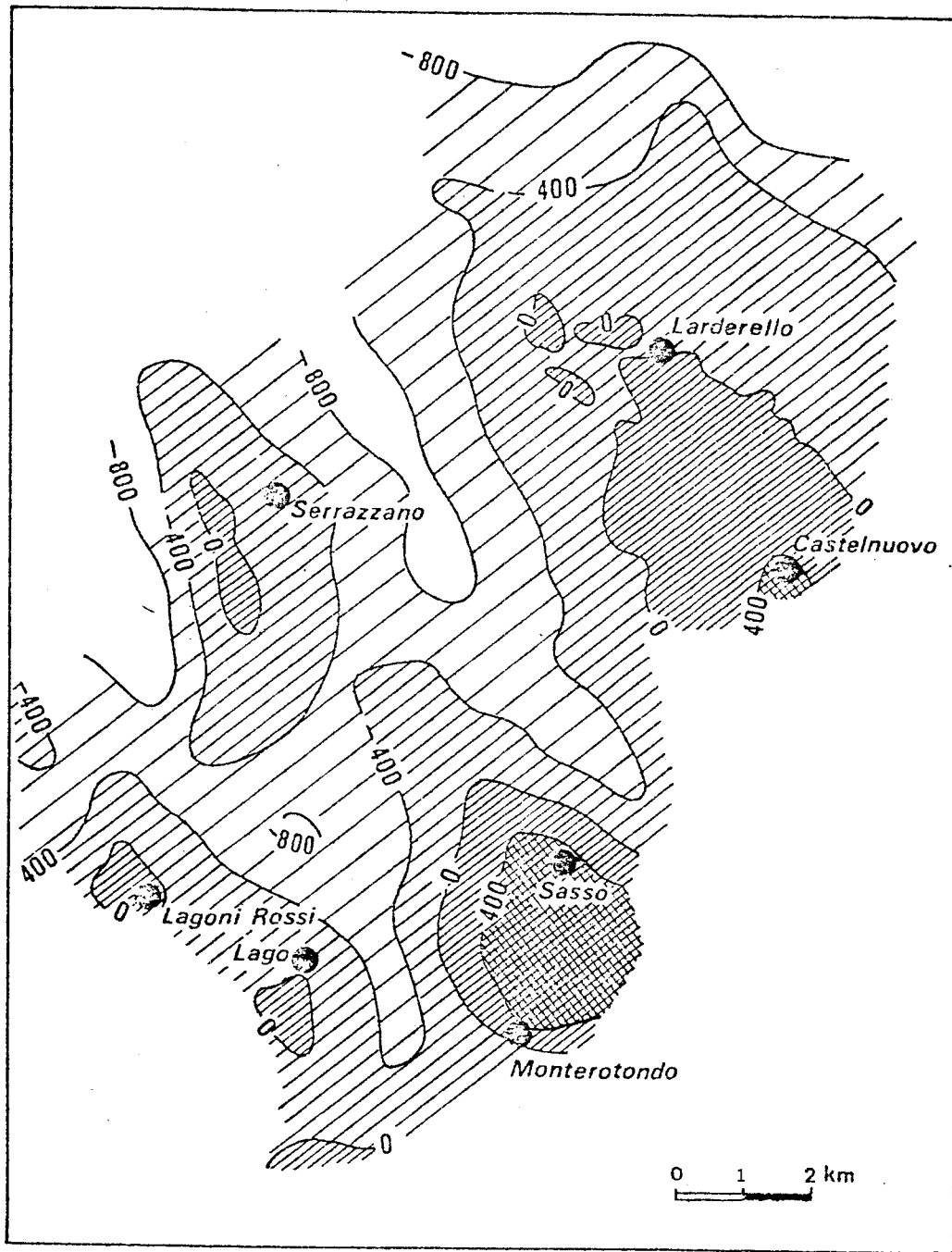


Figure 2 : Attitude of potential reservoir top in Larderello field (m a.s.l.)

FLUID FLOW IN GEOTHERMAL RESERVOIRS

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A discussion is presented of the material contained in Reference 1. This reference presents the results of an investigation of the fluid flow associated with pressure depletion in those geothermal reservoirs which are similar to oil and gas reservoirs. Geothermal reservoirs are often classified as either steam or hot water according to state of reservoir brine. These classifications imply the presence of only one phase; however, it is recognized that both liquid and vapor phases may be present initially or may develop as the pressure declines. This condition may involve the simultaneous flow of steam and hot water.

For two phase flow of steam and hot water the assumptions of small temperature and pressure gradients within the reservoir allow the simplification of the equations of heat and fluid flow.] This leads to a relation between the fluid pressure and the liquid saturation. Similar assumptions for single phase flow lead to an approximately constant reservoir temperature with fluid pressure decline.

The initial temperature and pressure in a geothermal reservoir determine its type.² The boiling point curve for pure water is presented by the dashed line in Figure 1. Dissolved salts in geothermal brines cause modification to this curve.³ Hot water reservoirs are represented by points to the right and below the curve as illustrated by initial point on curve A. Steam or single phase vapor reservoirs are represented by points to the left of the curve and points above the critical temperature, as illustrated by the initial points on curves B and C.

The solid lines in Figure 1 illustrate the behavior of closed geothermal reservoirs produced by pressure depletion with no water injection. The behavior of a hot water reservoir is illustrated by line A. Initially the hot water production causes rapid pressure decline since only liquid expansion and rock pore volume compressibility supply the driving energy. This essentially isothermal behavior continues until the boiling curve is reached. At this point the internal steam drive begins and a steam phase starts to build up within the reservoir. The temperature and pressure decrease along the boiling curve. When the steam saturation reaches the equilibrium saturation, steam begins to flow within the reservoir and hot water and steam are produced simultaneously. The steam saturation continues to build up as production continues with an ever-increasing steam-hot water ratio of the produced fluid. This process continues until the water saturation is reduced to the point where the hot water becomes immobile and hot water production stops. The boiling process continues with only saturation steam production until all the water is boiled away. At this point the temperature departs from the boiling curve and remains essentially constant as the pressure continues to decline, as illustrated by curve A in Figure 1. The produced steam becomes increasingly more superheated as the pressure

declines. The relatively high temperature at the end of pressure depletion indicates that considerable heat remains in the reservoir.

Curve B represents a steam reservoir which remains essentially isothermal with pressure decline. Only a small amount of heat initially in this type of reservoir is produced. Curve C represents a steam reservoir which is initially above the critical temperature and pressure. The temperature decline with pressure is slightly greater than reservoir B, but the overall temperature drop is small and most of the initial heat remains in the reservoir at pressure depletion.

The simplified equations of Ref. 1 do not strictly apply to conditions of gravity segregation of the steam and hot water. However, the insight obtained from the calculated results, coupled with the experience gained from oil and gas segregation in petroleum reservoirs, suggests the following behavior. Gravity segregation of the steam and hot water begins as soon as the steam phase begins to flow. Steam accumulation at the top of the reservoir increases the amount of steam produced from wells completed high in the reservoir. Correspondingly, wells completed low in the reservoir produce more hot water and less steam. Since the produced steam contains more heat than an equal mass of hot water completing wells high in the reservoir tends to increase the total heat produced under pressure depletion.

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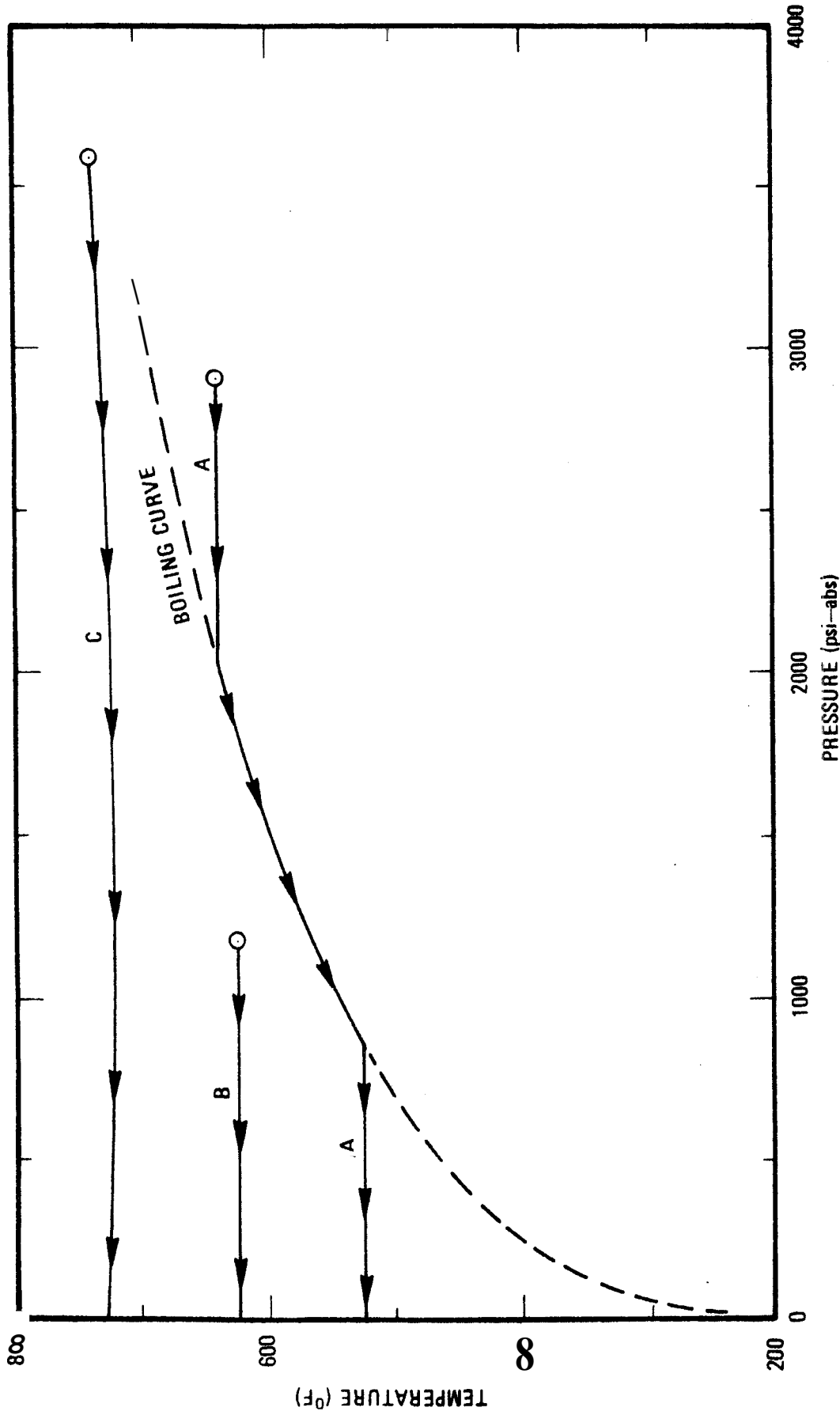


FIGURE 1
 AN ILLUSTRATION OF THE TEMPERATURE
 VS. PRESSURE PERFORMANCE FOR A HOT WATER
 RESERVOIR, CURVE A, AND TWO STEAM
 RESERVOIRS, CURVES B AND C.

FRACTURE FLOW IN GEOTHERMAL RESERVOIRS

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The following is a very brief summary of research in some topics of geothermal reservoir engineering and related matters which has been carried out by the writer during the past few years. A number of field data from geothermal reservoirs in Iceland will also be reported on.

Type of Reservoir Flow

Geological formations exhibit mainly two types of fluid conductivity or permeability, viz., (1) micropermeability due to very small intergranular openings and (2) macropermeability due to individual fractures and other major openings. The first type of permeability is associated with the Darcy type of flow which prevails in unfractured porous clastic sediments. It is characterized by laminar flow in the small openings and hence a linear relation (Darcy's law) between the pressure gradient and the specific mass flow. Fracture flow due to macropermeability prevails in igneous rocks, limestones and fractured sediments and is well known to be the most important type of flow in the majority of known geothermal reservoirs. A considerable literature exists on the theory of Darcy type of flow whereas much less attention has been devoted to fracture flow.

Borehole Productivity and Pressure Drawdown in Fracture Flow

Consider the case of a vertical borehole producing liquid phase flow from a horizontal fracture of constant width which is assumed to be small compared to the diameter of the hole. The solution of the differential equation for the pressure field in the fracture around the borehole is a simple task and gives the following result

$$p(r) = p_0 - \frac{q^2}{8\pi^2 h^2 \rho} \left[\frac{1}{r^2} + \frac{f}{hr} \right] \quad r > d/2 \quad (1)$$

where

- $p(r)$ = pressure in the fracture at the distance r from the borehole axis
- p_0 = undisturbed formation pressure
- q = mass flow of the borehole
- d = diameter of the borehole
- h = width of the fracture
- ρ = density of the liquid produced
- f = friction coefficient (dimensionless) of the fracture

At a given borehole pressure p_b , equation (1) gives for the mass flow

$$q = \pi h d \sqrt{\frac{2\rho(P_0 - P_b)}{1 + fd/2h}} \quad (2)$$

Equations (1) and (2) reveal two important facts. First, the pressure drawdown is very local. In most cases, the full formation pressure p_0 prevails at a distance less than 2 meters from the borehole axis. Second, fractures of very small widths give a high productivity. For example, a borehole of $d = 0.25$ meters cutting a fracture of $h = 10$ millimeters can at a pressure differential of $p_0 - p_b = 1$ atm produce about 100 kg/sec of water. These data are based on the assumption of turbulent flow. The above results can easily be extended to gas phase flows. Two-phase flows can be discussed on the basis of similar methods, but there is greater uncertainty as to the friction coefficient f .

Overall Permeability of Fracture Flow Formations

Flow in fractures is laminar at sufficiently small Reynold numbers. Slow large scale flow within fractured reservoirs with a sufficiently high fracture density can therefore quite often be treated on the basis of Darcy flow concepts and methods. Although the flow will generally be turbulent in the production zones around boreholes, these deviations are usually unimportant due to the small radius of the pressure drawdown.

There are some difficulties encountered in measuring or estimating the overall Darcy type permeability of fracture flow reservoirs. Nevertheless, useful estimates can often be obtained in the cases where borehole production is sufficiently variable to cause measurable fluctuations in the drawdown of the ground water surface. To illustrate the methodology involved, we will consider the following much simplified case.

Given a half-space of homogeneous and isotropic Darcy type permeability k and porosity ϕ , containing a stationary fluid with a horizontal surface and constant kinematic viscosity ν . A vertical well is drilled into the solid and pumping of the fluid is initiated at time $t=0$ from the depth H . Let the total volume of fluid produced during a given time interval be V , the resulting drawdown of the fluid surface at the well be d and the total drawdown volume be D . Assuming that d is very small compared with H , simple potential theoretical methods give the following estimate for the porosity of the solid

$$\phi = V/D = V/2\pi dH^2 \quad (3)$$

The permeability can be estimated by discontinuing pumping and observing the rate of recovery or velocity of upward movement of the fluid surface. Let the recovery process start with a drawdown d and an initial upward velocity u both measured at the well. Similar methods as used to obtain equation (3) give the following estimates for the permeability

$$k = uH\nu\phi/2gd \quad (4)$$

A variant of the method indicated has been used to estimate the permeability of the reservoir formations of the Reykjavik geothermal system in Iceland. The reservoir there is embedded in flood-basalts and has a base temperature of around 140°C. Since pumping is carried out in a group of fairly widely spaced wells, the right hand side of equation (3) cannot be used to estimate the porosity. Unfortunately, there are insufficient well data to estimate the total drawdown volume D directly. However, the average porosity of the flood-basalts can be estimated by other means and values of less than one % have been obtained. Using a value of 1/2% and the ground water surface recovery data from a single well, an estimate of the permeability of $3 \cdot 10^{-12} \text{ m}^2$ (MKS unit) or three Darcy is obtained. This is an apparent permeability which gives only an order of magnitude of the formation permeability.

Well Stimulation

Equation (2) above shows that borehole production from fractured rock can be stimulated by mainly two methods. First, by the lowering of the well pressure p_b which can be achieved by pumping. Second, by increasing the production opening or fracture width h at the well with the help of various types of fracturing techniques. Equation (2) indicated that the latter method is likely to be effective.

Both stimulation methods have been used with considerable success by the Reykjavik District Heating System in Iceland. Practically all producing wells of the system are now pumped. In many cases, hydraulic fracturing increases the well production by a factor of three to four.

Reservoir Stimulation

The productivity of geothermal reservoirs can be stimulated to a varying degree by the injection of water into the hot formations. Declining formation pressure and productivity of artesian reservoirs can be partially restored by a simple relatively low-pressure reinjection of effluent thermal waters. Partial stimulation of this type has the advantage of providing an efficient method of effluent water disposal. Moreover, geoheat production can be initiated from formations of low or negligible permeability by the injection of water at suitable locations. Of particular interest is the injection into local permeabilities provided by natural fractures, formation contacts, fault zones and dikes. The water is subsequently recovered by wells after having been in contact with a sufficiently large surface area of hot formations. Totally forced geoheat production of this type will in general require a more advanced technology. The economic feasibility has yet to be established and no such systems are now in operation.

From the theoretical point of view, reservoir stimulation, whether partial or total, involves a number of processes which have not been given much attention. Elastic, thermoelastic and convective effects are quite important but rather complex.

The geoheat productivity of fractures in formations of a given temperature can be estimated by fairly elementary means. Assuming operation times of 10 to 20 years and production temperatures within 10% to 20% of the formation temperature, a total of 10 to 20 metric tons of thermal water can be produced per square meter fracture area.

Pattern of Subsurface Flow

A very comprehensive survey of the isotope chemistry of natural waters in Iceland has provided interesting and important results on the overall pattern of ground water flow in the flood-basalt plateau of Iceland. The results indicate the location of the recharge areas of many geothermal systems in the country and show that isotope chemistry can be a very important tool in geothermal reservoir mechanics.

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RESERVOIR FACTORS DETERMINING THE FRACTION OF STORED ENERGY
RECOVERABLE FROM HYDROTHERMAL CONVECTION SYSTEMS

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The recoverability factors used to estimate resources of hydrothermal convection systems in Nathenson and Muffler (1975) are based on extracting the stored heat from a volume of porous and permeable rock, neglecting recharge of heat by either conduction or movement of water (Nathenson, 1975). The potential for heat recharge by conduction is neglected because it is very small compared to expected rates of production from any volume of rock greater than a few cubic kilometers. Likewise, for most of the hot-water systems of the United States, the natural discharge of thermal waters is low compared to reasonable production rates, and, accordingly, the potential for heat recharge by upflow of hot water to most reservoirs is probably low and can be neglected. The validity of this assumption can be assessed only after extensive production histories have been obtained for a reservoir. In those systems in which heat recharge by upflow of hot water is shown to be important, recoverability factors will have to be raised accordingly. Although the recharge potential of heat is neglected, the potential and, in fact, the need for cold water recharge are not.

Two possible methods for extracting energy from a liquid-filled volume of porous and permeable rocks are analyzed. The first method assumes that the porous, permeable volume is virtually closed to inflow of water and is produced by boiling to steam by using the energy in the rock. The second method assumes that natural and artificial recharge of cold water is used to recover much of the heat from the reservoir by means of a sweep process.

The fraction of stored energy recovered in the process of boiling the water in a porous volume of rock depends on the amount and pressure of the produced steam, which in turn are determined by the porosity and the initial temperature of the system. The pressure of the produced steam must be high enough to drive the steam through the porous medium and up the well at a significant rate; a reasonable assumption is that the pressure of the steam must be at least 8 bars. At a given reservoir temperature, this restriction constrains the range of porosity for which boiling is a viable recovery scheme. At 200°C, the upper limit for the porosity is about 0.05, and the fraction of stored energy obtained is about 0.2. At 250°C, the upper limit for the porosity is about 0.12, and the fraction of stored energy obtained is about 0.4. At porosities below this limit the fraction of stored energy obtained decreases with decreasing porosity in a nearly linear fashion. This production scheme is severely limited if there is significant recharge of water to the reservoir; recovery by boiling is then possible only if steam in the dried zone and water in the recharge zone are produced simultaneously in order to keep the zone of boiling moving into new regions of the reservoir. In summary, the restricted range of porosity, temperature, and recharge over which the boiling method will work limits its application to rather special, circumstances, in particular to vapor-dominated systems (see below).

The second production scheme involves the use of natural and/or artificial recharge of cold water to drive hot water in a reservoir to the producing wells. As the water sweeps through the hot rock, its temperature is raised by removing energy from the rock. The influence of heat conduction on this process takes place on two length scales. On the microscale of pores filled with water in a rock matrix, conduction makes the temperature of the rock and the pores come to equilibrium in a matter of a few minutes. On the scale of a volume of rock several hundred meters on a side having one zone of cold water and rock and a second zone of hot water and rock, conduction with no fluid movement spreads out an initially sharp change in temperature to a smooth transition of only 60 m thickness in a period of a decade. As cold water sweeps into a hot reservoir, conduction may be analyzed to a first approximation by superposition onto the movement of the temperature front, resulting in the premature breakthrough of cooler water into the hot zone. Another factor in the sweep process is the rotation of an initially vertical interface between cold water and hot water in a porous medium, owing to the difference in hydrostatic pressure on the two sides of the interface. Although this rotation is retarded by the energy stored in the rock, it also tends to cause premature breakthrough of cold water into the hot zone. These processes can be combined qualitatively to yield an estimate of energy that can be recovered from a reservoir of porous, permeable rock in a hot-water system.

Vapor-dominated reservoirs are assumed to contain steam as the pressure-controlling phase, with liquid water immobilized in the pores by surface forces (Truesdell and White, 1973). Production results primarily from the boiling of this pore water to steam, although in later stages there may be some boiling from an inferred deep water table. Because the liquid fraction in a vapor-dominated reservoir is small, the pressure and temperature of steam produced in the boiling process are generally close enough to the initial values for the system that ample pressure remains to drive the steam to and up the well. The fraction of stored energy that may be recovered, calculated by considering an energy balance for the boiling process, is critically dependent on the average liquid saturation.

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UTILIZATION OF GRAVIMETRIC DATA FOR ESTIMATION
OF HYDROTHERMAL RESERVOIR CHARACTERISTICS
IN THE EAST MESA FIELD, IMPERIAL VALLEY, CALIFORNIA

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This paper presents an attempt at correlating the observed phenomena of small positive gravity anomalies and self-sealing in some geothermal systems with possible geochemical, thermal and flow properties of such systems. In particular, the East Mesa geothermal area in the Imperial Valley, California shows up to 6 milligal positive residual gravity anomaly. Calculations show that the maximum depth to the center of gravity of the anomalous mass is a few kilometers, which is less than the depth to the basement in the area. We hypothesize that the presence of this gravity anomaly in the midst of a reasonably regular alluvial basin is due to deposition of minerals in pore spaces of sediments by upward rising plumes of geothermal water over geological time.

Facca and Tonani (1967) have explained the origin of hard, impervious caps in some geothermal systems, as being the result of precipitation of minerals in a water-convective system. Briefly restated, thermal water at depth has a certain dissolving power which is dependent upon temperature, pressure, pH and the nature of the rock. Because of the reduced density of the hot water which forces it to flow up, a convection system is created. The term "convection" is used loosely here, to signify heat transfer by this movement and not necessarily motion around a loop. Gravity data considerations favor either a once-through flow or a convective flow which has very larger horizontal components (Figure 1). As the water flows up through progressively colder and lower-pressure strata, it precipitates part of the ions which are carried in solutions. Such precipitates consist primarily of silica and calcite. Detailed investigations of the Dunes Anomaly (Elders, 1973) in the same geological basin, show that a series of quartzite layers occurs in the central part of the Dunes geothermal anomaly. No significant silica deposition has been reported in the East Mesa area, the subject of this study. However, the lithologic data gathered in the holes indicate increased calcite precipitation in the pore space (R. Fournier, personal communication).

Clear evidence for hydrothermal convection in the East Mesa Field is seen in any of the temperature-depth plots obtained by the U.S. Bureau of Reclamation in the various holes which were drilled in the East Mesa Field (Figure 2). The temperature gradient graphs show a sudden flattening at a depth of about 700 m. This may be interpreted as indicating the existence of a cap layer into that depth. Above the cap, the dominant heat transfer mechanism is conductive heat flow. Below this depth, convection predominates. This situation is in concordance with the models of Facca and Tonani (1967), or White (1965).

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A detailed gravity survey of the East Mesa Anomaly has been carried out by Biehler (1971) from which a residual gravity map (Figure 3) has been prepared. The gravity high corresponds to the temperature gradient high in the same area (Figure 4).

Mass-excess Calculations from Gravity Data

Hammer (1945) has shown that it is possible to calculate from gravity data the total anomalous mass giving rise to the gravity anomaly, without regard to the geometry or depth of the anomalous body, by performing a surface integration over the gravity anomaly area.

Performing that calculation with regard to the residual gravity anomaly at East Mesa, we estimate a net excess mass of about $(10 \pm 2) \times 10^9$ metric tons. This excess mass of about 10 billion tons of matter is believed to have been deposited in the alluvial strata directly as a result of the cooling effect of the shallower alluvium on the rising hot plumes of water. The basis for this assertion comes from the gravity data itself: trial half-width depth determinations show that the center of gravity of the anomalous mass must be within the sedimentary column. These determinations do not preclude however, that at least part of the gravity anomaly is due to basement uplift or due to density changes within the upper part of the basement rocks. Visual comparison with an unpublished aeromagnetic map of the area shows the absence of a magnetic anomaly at East Mesa. Such an anomaly would have been expected had the cause for the gravity anomaly been a basement uplift. One can attribute the absence of a magnetic anomaly to hyper-Curie-point temperature in the basement. We consider such a possibility as unlikely. Thus, we conclude that the gravity anomaly is largely due to hydrothermal mineral deposition within the sedimentary column, due to hydrothermal convection.

Assuming typical numbers for average porosity (20%) in the sedimentary column and rock matrix density (2.65 g/cm^3), we calculate that the excess mass has been deposited within a total volume of 19 km^3 of sediments. The East Mesa anomaly has an areal extent of 200 sq. km. Thus, over this area, the total thickness of the densified layers is estimated to be 95 meters or 311 ft., which is geologically reasonable.

Mass Convection of Water

Quartz solubility data indicate that up to 0.44 gram per liter of silica could precipitate out of solution when an originally silica-saturated solution precipitates the excess silica as it cools down from 250° to 100°C . Likewise, a significant amount of carbonate could precipitate out of a bicarbonate-rich solution as it decompresses. Assuming a mean of .4 gm/liter precipitation, a mass excess of 10 billion tons of precipitate would have required about 25 trillion tons of thermal water to have circulated through the system. The water flow must be primarily vertical, to account for the observed residual gravity anomaly. As the rising plume of water encounters an impermeable boundary, it is deflected laterally in all directions. The

upward flow of the geothermal water results in deposition of minerals, either due to cooling (silica) or to decrease in pressure (calcite). The zero contour on the residual gravity anomaly is an expression of the outermost possible limit of the lateral extent of precipitation. The actual limits might be closer to the center of the rising plume.

A flow model of "once-through" is preferred to a model of toroidal circulation. The "once-through model" is based upon the assumption that hot water, mobilized in the igneous basement or in the deeper part of the sedimentary strata, moves through fractures and shear zones upward above the hot spot, in a heat-pump-like process. Having reached its apex, the water flow is dissipated laterally in all directions. The toroidal circulation model, on the other hand, may pose the problem of mass balance, which theoretically at least would minimize the size of any residual gravity anomaly. This is because in such a model, the dissolved matter at the base of the convecting cell is deposited above it, hence no mass is gained or lost. Of course, the shallow excess mass would give rise to a higher gravitational attraction, but Gauss' theorem shows that if the integration of the surface integral is carried over the area of the source and the sink, the mass loss and deficiency would balance out. On the other hand, if the source of the mass is from a very large area, it would not affect Hammer's surface integral which is carried out over a smaller area.

Figure 5 shows the rate of water convection over the entire East Mesa Anomaly for different assumed ages of the system. The minimum upward flow is about $0.8 \text{ m}^3/\text{sec.}$ for a one-million year old system, to $80 \text{ m}^3/\text{sec.}$ for a 10,000 year old geothermal system. Investigations of other geothermal systems suggest that the life of a geothermal system lies typically in the range of 10,000-50,000 years (White, 1965; Ellis, 1970). For a 50,000 year old system the vertical convection rate had to be of the order of 8,600,000 barrels/day (1,400,000 tons/day). Even if we assumed that there is an order of magnitude error in overestimating the contribution of the sediments to the total gravity anomaly, these numbers remain quite impressive. These numbers indicate that vertical permeability is a major factor in the flow regime of a geothermal system.

If this vertical flow had taken place over 50,000 years across the entire horizontal extent (200 square km) of the East Mesa anomaly, average macroscopic velocity should have been $0.8 \times 10^{-5} \text{ cm/sec.}$ An average value of the vertical permeability can then be calculated from Darcy's law as:

$$k = - \frac{\nu \mu}{\frac{dp}{dz}} \text{ (in Darcy units) , where}$$

k = vertical permeability (Darcy)

ν = macroscopic velocity = $0.8 \times 10^{-5} \text{ cm/sec.}$

μ = viscosity = 0.2 centipoise (a value typical for the salinity, temperature and pressure of the East Mesa formation water)

$\frac{dp}{dz}$ = vertical pressure gradient due to buoyancy of hot water surrounded by cold water = -0.0002 atm/cm (gradient caused by the maximum temperature difference of 150°C between hot and cold water).

This gives a value $k = 8$ millidarcy. However, convective flow must have taken place across a far smaller cross-section than the entire 200 sq. km. Assuming that only one percent of the cross-section was involved in convective flow, the average vertical permeability is calculated to be 800 millidarcy. A vertical permeability of this magnitude through a faulted or fractured conduit is not inconceivable. If the estimated flow rate (Q) of $16.0\text{m}^3/\text{sec}$ takes place through a vertical fault of lateral extent L , then the required fracture width (h) along the fault is given by:

$$h^3 = \frac{12\mu Q}{Ldp/dz}$$

For $L = 1$ kilometer, using consistent units, we calculate $h = 2.6$ mm. Thus, a one kilometer long vertical fault along which an average fracture width of 2.6 millimeters could have been an adequate flow conduit.

No hot springs or other geothermal surface manifestations exist at the East Mesa Anomaly. It is possible, however, that hot springs, have flowed to the surface in the geologic past. We conclude from the foregoing discussion that although geysers, hot springs and fumaroles may perhaps be a spectacular demonstration of the great heat reservoirs which are located at a shallow depth below the earth's surface, the absence of these geothermal manifestations need not be taken as a sign of absence of tappable geothermal energy at an economic depth of exploration. Very large thermal water flows, of the same order of magnitude as the more spectacular geysers, may be circulating at shallow depths below the earth's surface, when hydrogeological conditions do not favor outflow to the surface.

Convective Heat Transfer

We can calculate the amount of heat convectively transferred by the above system. Assuming that the temperature drop required for precipitation of the excess mass at the East Mesa Anomaly is 150°C , the total heat transferred convectively with the water since the birth of the East Mesa geothermal system is about 3.8×10^{21} calories, taking the mass flow of water as 25×10^{12} tons. This is much greater than the value given by White (1965) for the heat stored to a depth of 3 km in some typical hot springs systems, which he calculates to be of the order of 2×10^{20} calories.

The area of the East Mesa geothermal anomaly is about 200 sq. km. Hence, the convective heat transfer of the geothermal anomaly has been about 1.9×10^9 cal/cm² from the birth of the East Mesa geothermal system to the present.

Figure 5 contains also a plot of heat flow (μ cal/cm²/sec) versus possible age for the East Mesa Anomaly. It is noted from this figure that for an assumed age of 50,000 years for the East Mesa system, the convective heat flow would be 1200 heat flow units (HFU). This is about 200 times the estimated present conductive heat flow for the anomaly.

The reported conductive heat flows for the geothermal anomalies in the Imperial Valley vary between 7-17 HFU (Rex, 1966; Helgeson, 1968). For the East Mesa Anomaly, the conductive heat flow is estimated to be 4-6 HFU (Combs, 1971). The difference between the lower observed heat flow and the estimated high convective heat flow rate may be due to the possibility that as self-sealing progresses, the vertical component of convective water flow becomes minor, while lateral dissipation of heat becomes more important. Eventually heat may be totally dissipated laterally into large aquifers at great depth without substantially increasing observed heat flow rate at the ground surface.

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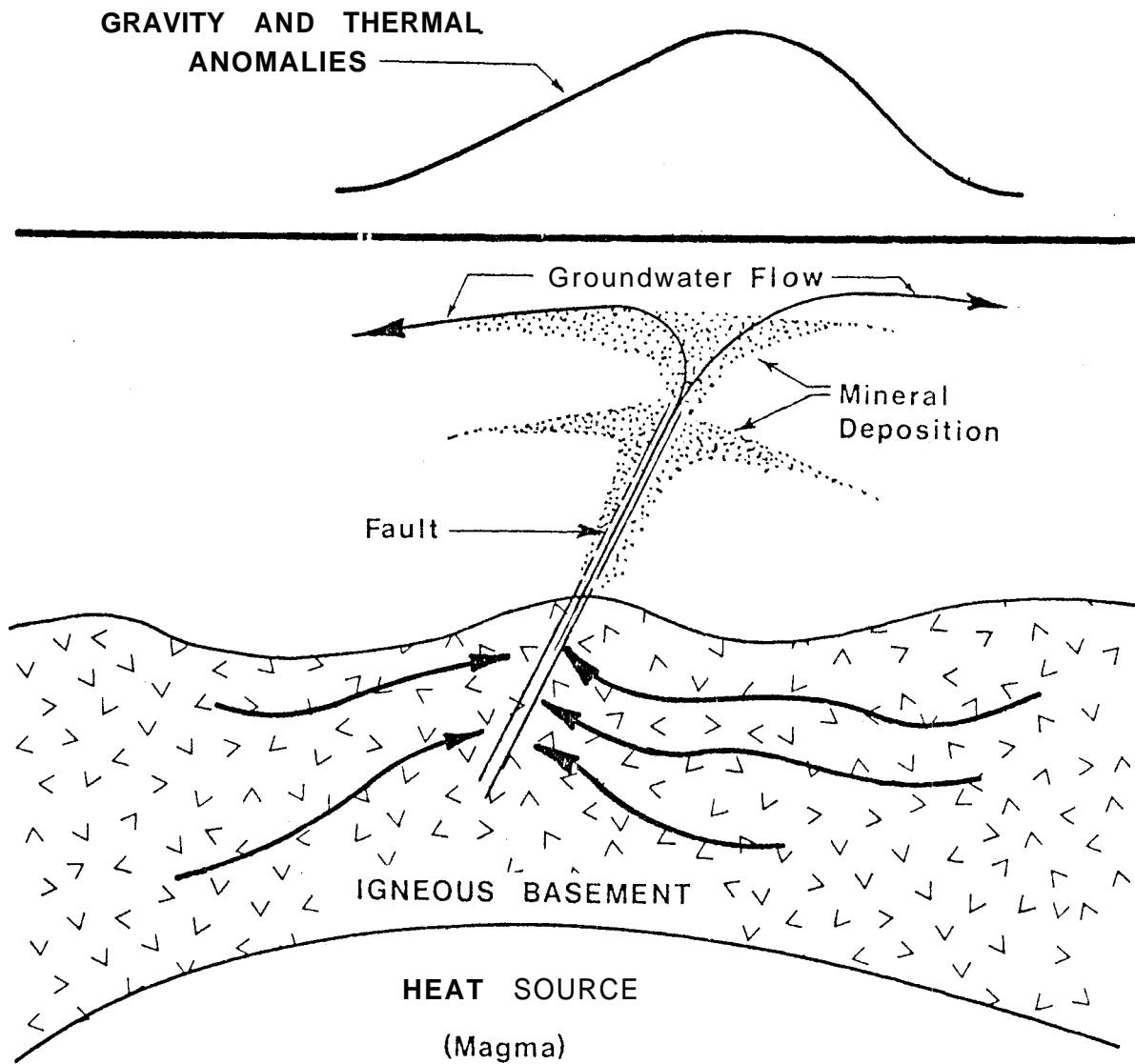
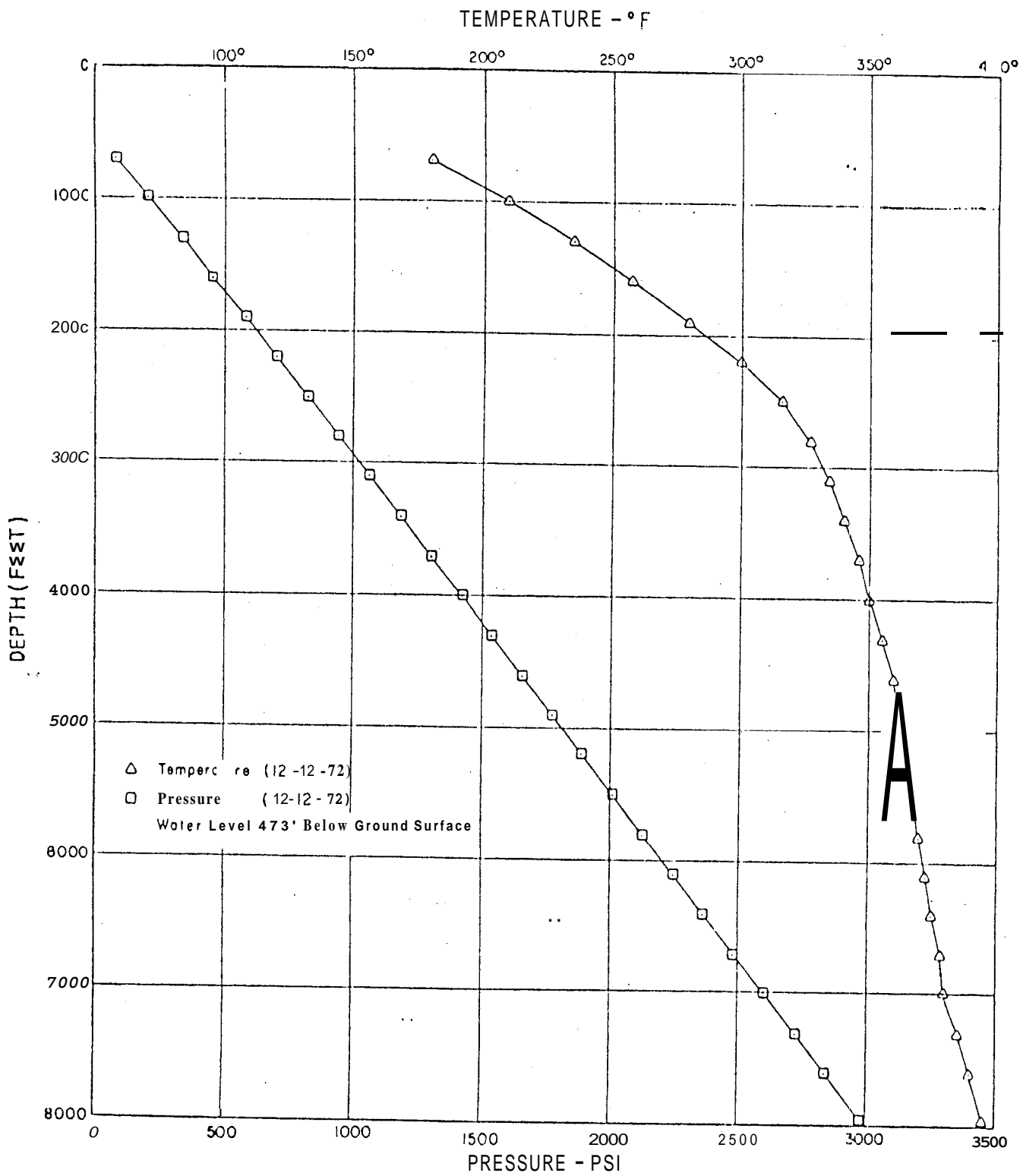


Figure 1. Conceivable flow model for a self-sealing hydrothermal system, with the associated gravity and thermal gradient anomalies.



TEMPERATURE & PRESSURE IN WATER COLUMN
MESA 6-1, IMPERIAL VALLEY, CALIFORNIA

Fig. 2

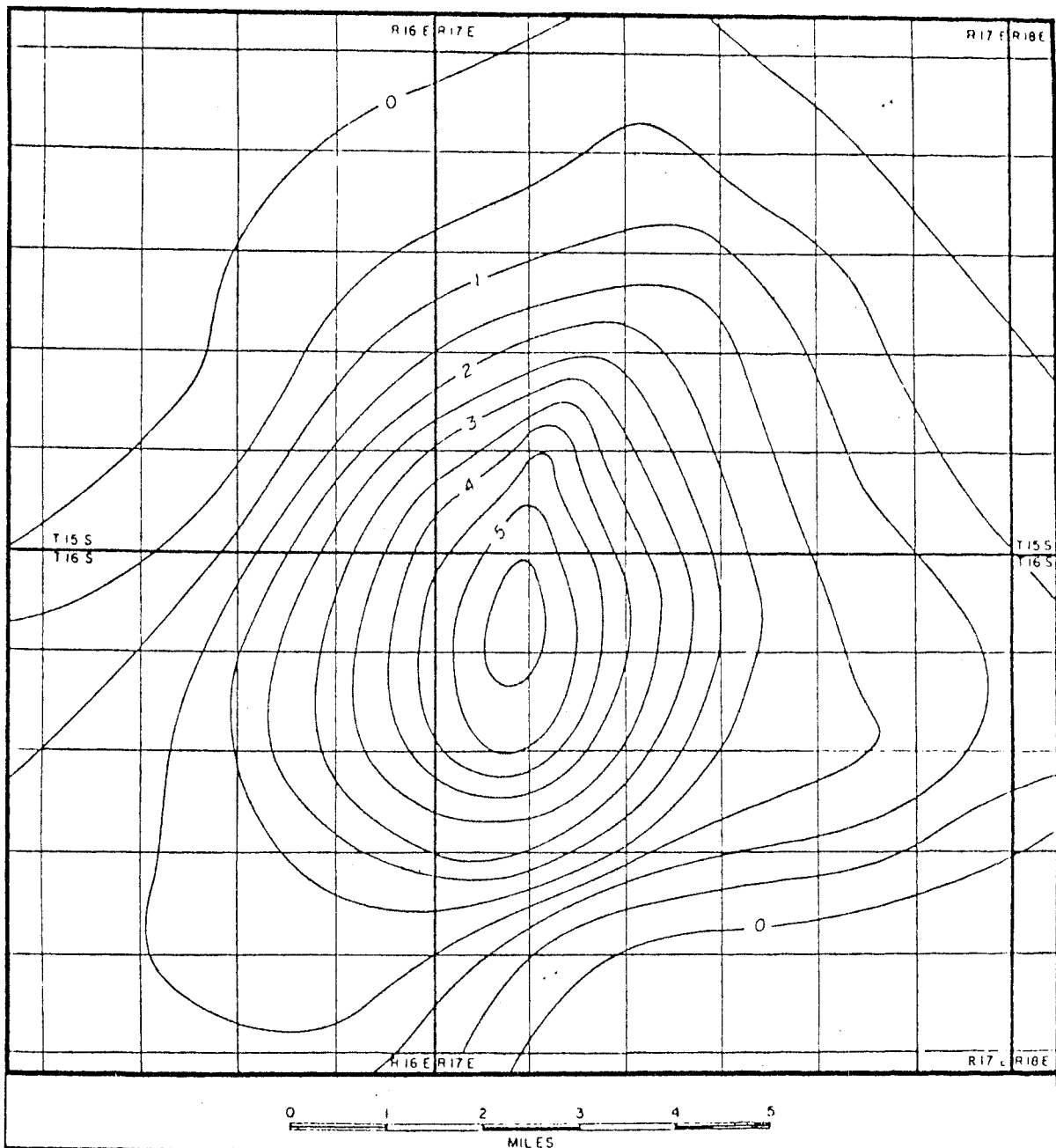


Figure 3. Residual gravity map of the Mesa area (Biehler, 1971).
 Contour Interval 0.5 mgal. CJ = .5 mgal.

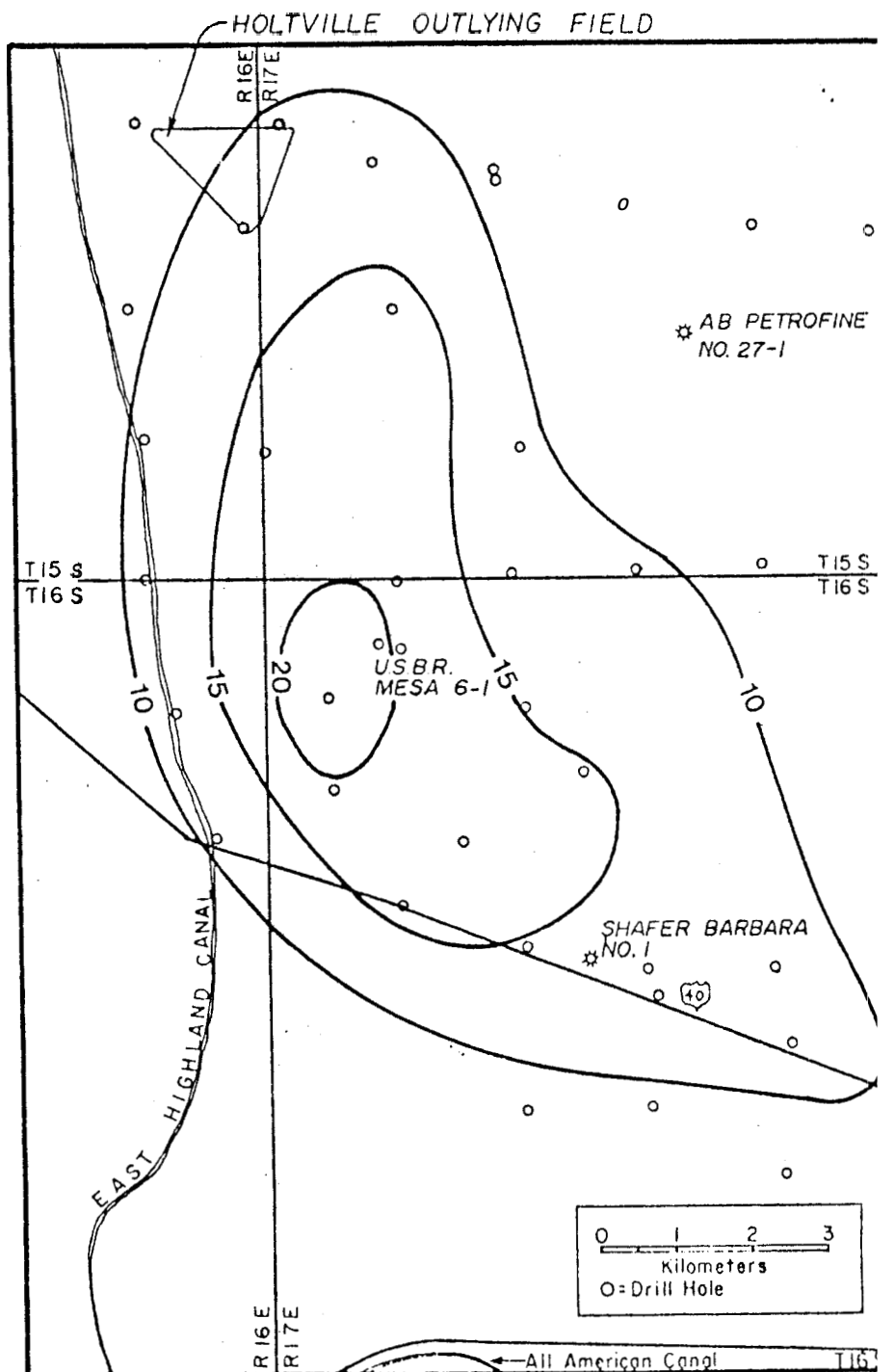
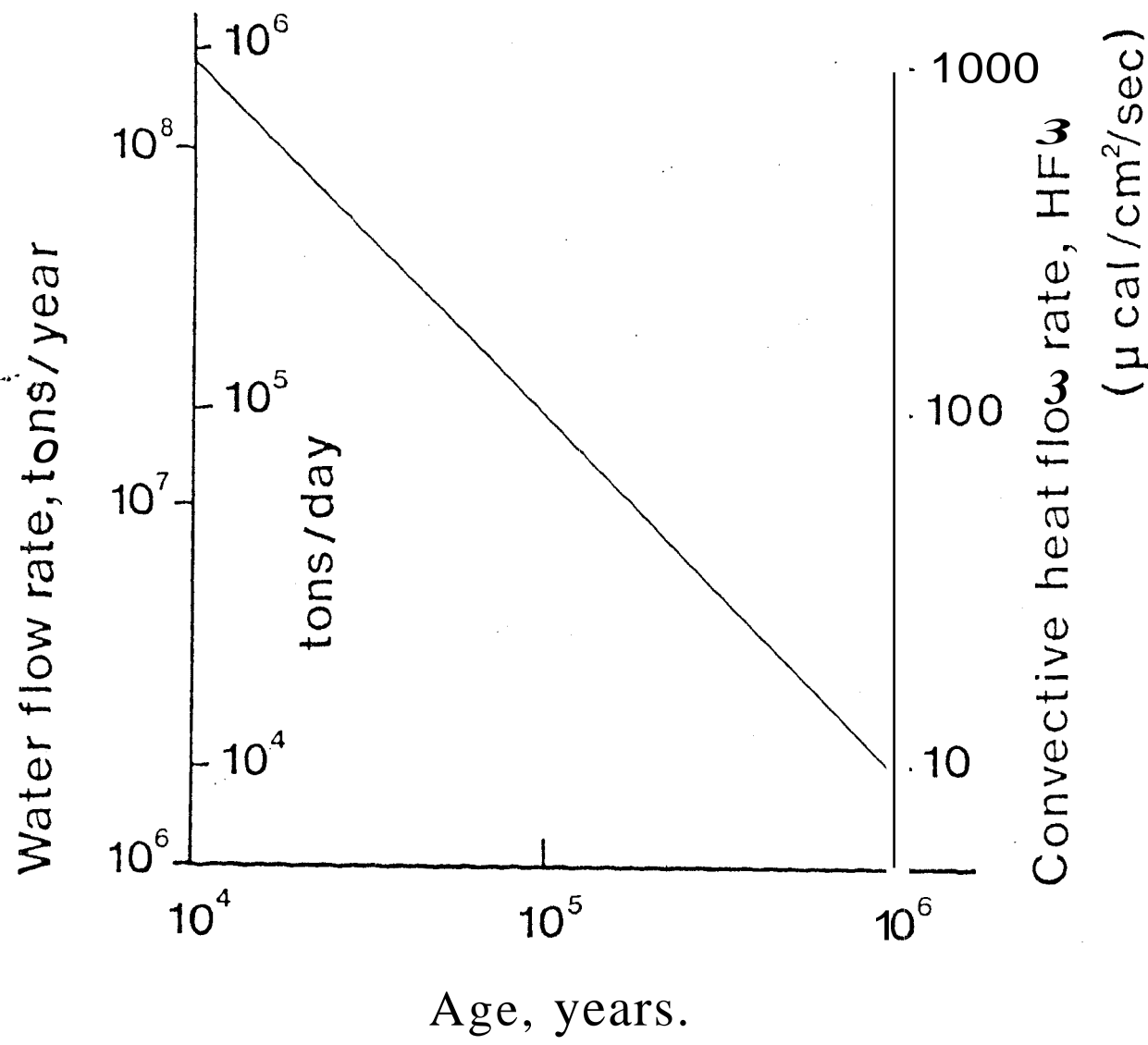


Figure 4. Temperature gradient map of the East Mesa anomaly (Combs, 1971; based partially on data by Rex, 1970).



Estimated water and convective heat flow rates of East Mesa hydrogeothermal system

Figure 5.

AN INVESTIGATION OF SCREENING GEOTHERMAL PRODUCTION
WELLS FROM EFFECTS OF REINJECTION

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Reinjection of used geothermal liquids into the producing reservoir has been proposed by several investigators as an effective way to avoid disposal problems and to reduce the possibility of land subsidence in the reservoir area.

However, after a length of time, the reinjection water will break through at the production well, which will no longer be able to maintain its original temperature. Gringarten and Sauty¹ have developed a simple steady-state model to study such a system of many production and injection wells, capable of calculating the temperature decrease as functions of time. The present paper describes a possibility of retarding the breakthrough time and reducing the temperature drop by means of screening wells.

The basic physical idea is as follows. Consider a doublet of one production and one injection well. Streamlines will go from the injection to the production well. The earliest streamlines that reach the production well will correspond to those close to the straight line leading from the injection to the production well. Now if we have an extra screening well on this line in between the two wells, which extracts fluid and puts it back into the injection well, then these earliest streamlines will be "picked up" by the screening well and prevented from arriving at the production well. In this way, not only is the breakthrough time increased, but also the rate of temperature drop is reduced. Besides the temperature difference of the reinjected water and the reservoir, two dimensionless parameters enter into the problem, the rate of extraction of the screening well relative to that of the production well, γ , and the position of the screening well, α , defined as the distance of screening well from the production well divided by the separation of the doublet. It is easy to see that the screening effect will be increased with an increase of γ and a decrease of α .

We have calculated the breakthrough time as a function of α and γ , with α ranging from 0.1 to 0.9 and γ from 0 to 1.5, and we found that it is possible to increase the breakthrough time by as much as a factor of 2 in certain cases. Hence, given a case of a doublet whose breakthrough time is 20 years, it is possible to place a screening well of appropriate flow rate such that the production temperature is not affected at all for 40 years.

It is easy to extend the problem to include effects of the natural areal flow in the reservoir. We consider a case that Gringarten and Sauty studied, in which they looked at the possibility of siting a doublet in a heavily-built area for space heating and cooling. There is a strong areal flow and

by placing the injection well downstream, they found that there will be no interflow (i.e., infinite breakthrough time) if the two wells are placed 965 meters apart. But the maximum practical separation is only 300 meters in the direction of areal flow. Thus they have to employ other techniques. However, by our calculations with a separation of 300 meters, we found that it is possible to obtain zero interflow with the production well by placing a screening well 90 meters from the producing well with a flow rate 1.4 times the producing rate.

Further calculations are made on the steady-state flow model of Gringarten and Sauty to study the temperature decrease rate for systems with screening wells. Not only are we able to calculate the streamlines and thermal fronts, but the temperatures at the wells as a function of time are calculated. Figure 1 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 streamlines, 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 which is somewhat meaningful, we take a case of a doublet without screening in which the production and reinjection rates are each $2Q$, 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 $\gamma = 1$ and $\alpha = 0.1$) 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.

In conclusion, we believe that a retardation of breakthrough time and a reduction of the rate of temperature drop at the production well can be obtained by means of an (extraction) screening well. In our calculations, we found that a very significant factor in energy gained can be realized. However, we have not yet made a detailed economic feasibility study taking into consideration the expenses of digging the extra screening well. Initial discussions indicate that with certain arrangements and parameters, such screened systems may have significant economic advantages.

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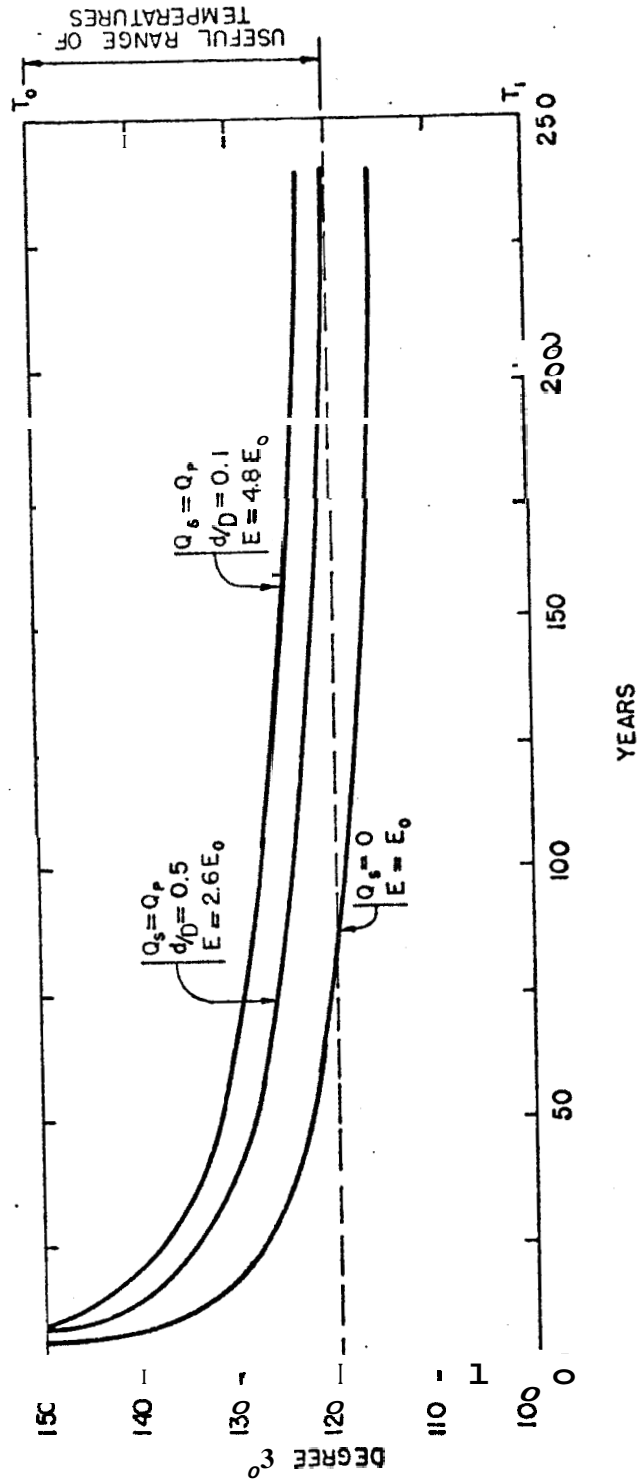
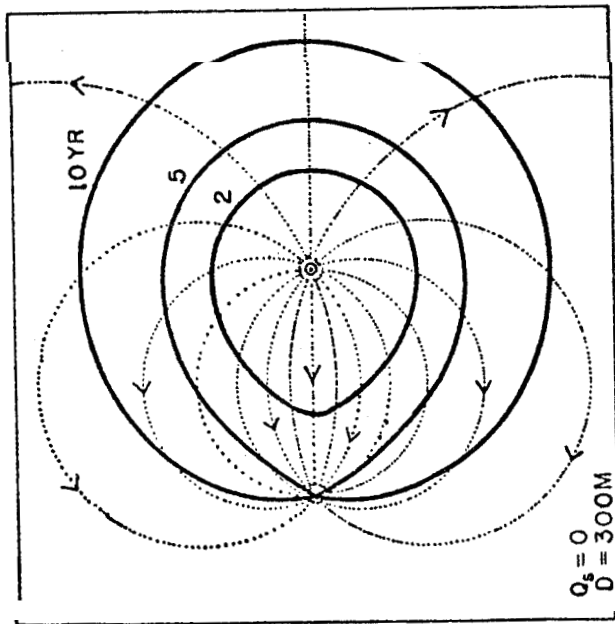
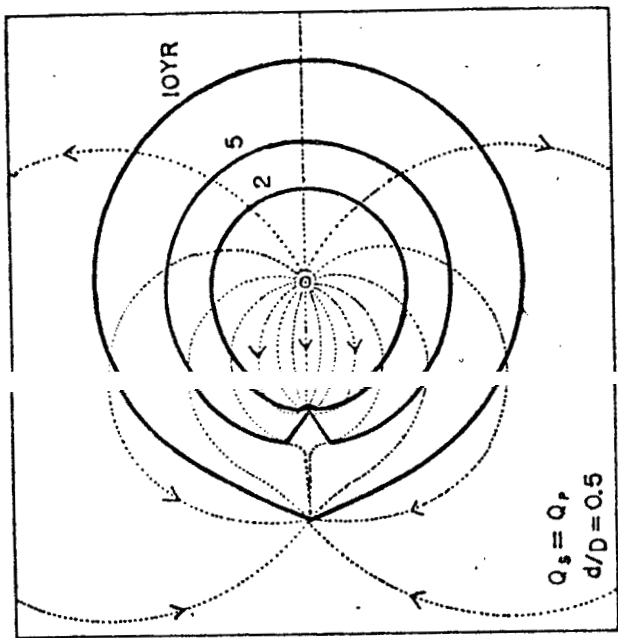


Figure 1. The top half of the figure indicates the streamlines (dotted lines) and the thermal fronts (solid lines) of the doublet system with and without screening. The lower half shows the temperature at the production well as a function of time in three cases, (a) no screening well, (b) screening well 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.

LAND SURFACE SUBSIDENCE ASSOCIATED WITH GEOTHERMAL ENERGY PRODUCTION

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Land subsidence, sometimes observed during oil field production, is potentially a serious problem in geothermal energy production, particularly of liquid-dominated hydrothermal and geopressured fields. In the Imperial Valley--one of the most promising liquid-dominated geothermal regions in the United States--extensive subsidence could damage irrigation canals and other surface structures. Even if the subsidence is confined to the production area, special measures may be necessary to protect the geothermal extraction and electrical generating equipment. Subsidence is, in general, caused by the compaction of the semi-consolidated and unconsolidated strata of the reservoir as the effective overburden stress is increased due to fluid withdrawal. In some oilfields (e.g., the Wilmington oil field in the Los Angeles basin), injection of water into the formation has been successfully employed to reduce subsidence. Subsidence is potentially a more serious threat in geothermal production due to the much larger volume of fluid required to produce a given amount of energy. Fluid reinjection, while undoubtedly useful, is not a universal remedy to subsidence, for several reasons. First, while some of the compaction is elastic and may be recovered, it is well known that irreversible pore collapse (permanent deformation) also accompanies fluid withdrawal. Second, due to the nature of the electrical generating process, only a fraction of the produced fluids will be available for reinjection; the reinjection fluid may, of course, be augmented by surface water to make up the volume deficit. Third, reinjection (especially of concentrated brines which are characteristic of some Imperial Valley geothermal anomalies) may not always be practical at (or near) the same horizontal and vertical location as production. Reinjection at a sufficient lateral distance from the producing well may result in uneven surface displacement. Furthermore, subsurface fluid injection may, by increasing pore pressures, tend to increase levels of seismic activity. Many geothermal reservoirs (including those in the Imperial Valley and the geopressured systems in the Gulf Coast) lie in regions of extensive faulting--thus, the danger of earthquake triggering cannot be discounted.

MATHEMATICAL MODEL

All of the geohydrological effects described above involve mechanical interactions between the rock and fluid components. The theoretical model, developed within the framework of the Theory of Interacting Continua, describes the thermomechanical response of the rock and fluid (water and/or steam) composite material in terms of the isolated components. The stress-

strain equations for the rock matrix are coupled with the diffusion equations for the fluid. The microscale details of the pore/fracture network in the rock are ignored, but the fluid pressures and the stress field in the rock matrix are permitted to assume distinct values within each computational region for the composite. The fluid flow equations and their solution is discussed elsewhere (Pritchett, ~~et al.~~, 1975). In this paper, we shall confine our attention to rock response under a given fluid pressure history.

Assuming that (1) the rock matrix undergoes only small deformations and (2) the reservoir behaves in a quasi-static manner during production/injection, the equation expressing momentum balance for the rock matrix can be written as follows:

$$-\nabla[(1-\phi)P_s + \phi P] + \text{div } \underline{\underline{\xi}} + [(1-\phi)\rho_s + \phi(1-S)\rho_\ell + \phi S\rho_v] \underline{\underline{g}} = 0 \quad (1)$$

where

$\underline{\underline{g}}$ = Acceleration due to gravity

p = Fluid pressure

P_s = Solid pressure

S = Relative vapor volume [= $V_v/(V_v + V_\ell)$].

$\underline{\underline{\xi}}$ = Deviatoric stress tensor for porous rock.

$V_v(V_\ell)$ = Vapor (liquid) volume.

ρ_i = Density ($i=s$, solid; $i=\ell$, liquid; $i=v$, vapor)

ϕ = Porosity

It is necessary to complement Eq. (1) with suitable constitutive relations for the rock matrix.

The bulk strain-rate tensor for rock $\dot{\underline{\underline{\xi}}}$ is given by:

$$\dot{\underline{\underline{\xi}}} = \frac{1}{2} [\nabla \underline{\underline{v}}_s + (\nabla \underline{\underline{v}}_s)^t] = \frac{\dot{\underline{\underline{\epsilon}}}}{3} \underline{\underline{I}} + \dot{\underline{\underline{e}}} \quad (2)$$

where $\dot{\underline{\underline{e}}}$ denotes the deviatoric part of the strain-rate tensor. Bulk volumetric strain $\underline{\underline{\epsilon}}$ is related to the rock grain (or effective) volumetric strain ϵ^e through the relation:

$$\epsilon^e = \frac{\rho_{os}}{\rho_s} - 1 = \left(\frac{1-\phi}{1-\phi_0} \right) (1 + \underline{\underline{\epsilon}}) - 1 \quad (3)$$

The rock grain may be assumed to be a linear thermoelastic material over the range of temperatures and pressures encountered in geothermal reservoirs.

$$P_s = -K_s (\epsilon^e - 3 \eta_s T_s) \quad (4)$$

where K_s (η_s) denotes the bulk modulus (coefficient of linear thermal expansion) for the rock grain. Additionally, we will postulate that the shear stresses S are linearly related to shear strains e through Hooke's law:

$$S = 2 \mu_p e \quad (5)$$

where μ_p is the shear modulus of the porous rock.

Porosity ϕ depends in a complex manner on the current state of stress (σ^s, P), stress history, temperature and the rock type. Consolidated rocks generally exhibit greater compaction at elevated temperatures than they do at lower temperatures; the effect of temperature is not, however, so significant in loose or unconsolidated sands. Shear stresses S , depending upon the rock type, may contribute to compaction, may lead to dilatancy, or may have no significant effect upon ϕ . Let us consider the case when ϕ does not appreciably depend on S ; in this case porosity ϕ depends on a close approximation only upon $P_c - P$ (Garg and Nur, 1973):

$$\phi = \phi_0 [1 + \alpha(P_c - P)] \quad (6)$$

where

$$\alpha = \alpha(P_c - P) = \frac{1}{\phi_0} \left[\frac{1}{K_s} - \frac{1 - \phi_0}{K} \right] \quad (7)$$

Here $K(P_c - P)$ is the bulk modulus of the porous rock and has different values during loading (increase in effective pressure $P_c - P$) and unloading (decrease in effective pressure $P_c - P$).

The theoretical model discussed above requires K , μ , K_s and η_s as empirically determined input functions. Although most of these properties can be obtained from standard laboratory tests on cores, it should be noted that the reservoir behavior is frequently governed by fractures, formation inhomogeneities, and other large scale features such as faults. It, therefore, becomes important to supplement the laboratory measurements by suitable field data. In particular, the bulk and shear moduli (K , μ_p) of reservoir rocks should be obtained from seismic measurements.

COMPUTER CODE AND APPLICATIONS

To solve the rock response equations (1-7), a finite element solid equilibrium code, **STAGR** (Static Analysis of Geothermal Reservoirs) has been developed. Like any such finite element code, it is basically a program for solving the problem of a loaded linear elastic continuum; however, materially nonlinear problems may be solved by iteration, using effective elastic moduli ("tangent" or "secant" moduli) in the elements. Due to the very small matrix displacements expected in geothermal reservoir calculations, only

material nonlinearity, and not geometric nonlinearity, has been included. In addition to the usual features found in finite element continuum codes, STAGR can solve problems involving nonsymmetric stress-strain relations (necessary for problems involving incremental loading of materials which undergo plastic deformation). This requires the use of a nonsymmetric stiffness matrix. Further details of the finite element code are given elsewhere (Pritchett, et al., 1975).

The STAGR equilibrium code has been used to perform 2-D calculations of the rock response to production of a hypothetical geothermal reservoir. Details of the reservoir geometry and elastic properties, and the assumed production strategy are given in Pritchett, et al. (1975). We will here merely summarize the significant results.

For the present reservoir, the principal stress directions at $t = 0$ (i.e., prior to fluid production) were almost coincident with the x (horizontal) and y (vertical) directions. Changes induced in σ_x , σ_y and σ_{xy} by the production of reservoir fluids were monitored as a function of time. It was found that both $\text{MAX } |\Delta\sigma_y|$ and $\text{MAX } |\Delta\sigma_{xy}|$ are much smaller than $\text{MAX } |\Delta\sigma_x|$. Thus, as a result of fluid production, σ_x becomes much less compressive whereas σ_y is essentially unaltered. This has interesting implications for reservoir stability. Large reductions in the magnitude of σ_x without corresponding reductions in σ_y can lead to rock failure and growth of normal faults. Surface manifestation of these phenomena may be localized reservoir slumping, and increased seismic activity.

Surface displacement contours show that the central portion of the reservoir subsides almost uniformly. Elsewhere, the vertical motion is accompanied by significant horizontal movement. Experience from oilfields (e.g., Wilmington oil field in Los Angeles basin) indicates that horizontal motion may cause even more severe damage to surface installations (e.g., roads, bridges, and buildings) than that caused by vertical subsidence. Thus, in order to assess the possible environmental impact of fluid production from geothermal reservoirs, it is necessary to take into account both horizontal and vertical motions of the ground surface.

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PRESSURE AND TEMPERATURE BUILDUP IN GEOTHERMAL WELLS

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Two-phase flow and heat transfer influence the pressure-time response of hot-water wells. The methods developed for pressure buildup analyses in oil, gas, and cold water reservoirs are not completely applicable in hot-water reservoirs.

Mathematical synthesis is necessary to build existing two-phase flow theory, heat transfer theory and steam thermodynamics into a system for analyzing hot-water well pressure transients that is equivalent to methods available for oil and gas reservoirs.

HOT WATER FLASHING IN THE RESERVOIR CAUSES TEMPERATURE CHANGES

When flowing reservoir pressure falls below the saturation pressure corresponding to the reservoir temperature, hot water flashes in the reservoir. As the hot water flashes, fluid temperature drops in response to the prevailing pressure. Consider conditions prevailing in a hot-water well:

Static reservoir temperature = 593°F
Static reservoir pressure = 1823 psia
Steam saturation pressure
corresponding to 593°F = 1464 psia

Because the reservoir pressure is greater than the saturation pressure, there is no steam in the static reservoir conditions.

Bottom-hole flowing pressure = 450 psia

The bottom-hole flowing pressure is less than the saturation pressure; therefore, as it flows toward the well, part of the hot water flashes into steam. From thermodynamic considerations, the temperature of the steam-water mixture must correspond to 450 psia.

Saturation temperature
corresponding to 450 psia = 456°F

Thus the fluid temperature has declined from 593°F to 456°F. But the rock temperature was 593°F. The difference in the rock and the fluid temperature causes the heat to flow from the rock to the steam-water mixtures.

RATE OF HEAT TRANSFER FROM TEMPERATURE BUILDUP

During pressure buildup measurement in a hot-water well, temperature usually is measured along with the pressure. An interpretation of the temperature buildup can give us the rate of heat transfer in the rock, by conduction, toward the wellbore.

Fig. 1 shows temperature buildup graph in a hot-water well. The slope on this graph is given by the following relation:

$$m = \frac{2.303 q}{4 \pi kh}$$

where q = rate of heat transfer, Btu/hr
 k = thermal conductivity of the rock, Btu/hr-ft-°F
 h = formation thickness, ft
 m = slope on the semi-log paper, °F/cycle

The slope on Fig. 1 is 48°F/cycle. Using $k = 2$ Btu/hr-ft-°F:

$$\frac{q}{h} = (48) (4\pi) (2) / 2.303$$
$$= 525 \text{ Btu/hr-ft.}$$

This provides evidence of heat transfer. During the production period, this heat is available to raise the enthalpy of the produced fluid.

The above calculation of the heat transfer rate assumes heat transfer to the wellbore by conduction only. In fact, the heat is transferred both by conduction and by the fluid transport. Thus the component of heat transferred by conduction alone will be less than 525 Btu/hr-ft.

FLASHING IN THE RESERVOIR GIVES RISE TO A REGION OF TWO-PHASE FLOW

The bottom-hole flowing pressure of this hot-water well is 450 psia whereas the steam saturation pressure corresponding to the static reservoir temperature of 593°F is 1464 psia. The reservoir pressure increases away from the wellbore from 450 psia to the original pressure of 1823 psia. At some distance from the wellbore, the pressure will exceed 1464 psia and that point will mark the boundary between two-phase and single-phase flow.

FOR PRESSURE ANALYSIS, A STRAIGHT LINE CANNOT BE FOUND

Fig. 2 presents pressure transient data, measured at the same time as the temperature data, Fig. 1. Pressure, on Fig. 2, is plotted as a function of $\log [(t + \Delta t) / \Delta t]$ for an oil reservoir Horner-type analysis. For this analysis, a straight-line portion of the graph is selected; its slope is inversely proportional to reservoir permeability.

This buildup lasted 550 hours. But we see a curve rather than a straight line. Unfortunately, there are gaps in the observations. But data gathering is a part of the problem in hot-water wells.

The buildup data presented in Fig. 2 do not show wellbore fill up or linear flow effects on a log-log type curve match. This makes it difficult to find the onset of radial flow or, in other words, the start of a semi-log straight line. One could draw more than one straight line through the data on Fig. 2. Although I have drawn a line of slope 121 psi/cycle, I cannot find sound justification for this line.

STEAM-WATER INTERFACE TENDS TO MASK THE END OF THE STRAIGHT LINE

Drainage areas in hot-water wells generally have two boundaries. The first boundary is the steam-water interface which is created as a result of the flowing reservoir pressure falling below the saturation pressure. The extent of the steam-water boundary is controlled, among other factors, by the

flowing pressure, the initial reservoir pressure and temperature, and the rate of heat transfer from the rock to the fluid. The second boundary is the drainage boundary of the system; it could be closed, held at a constant pressure, or a mixed boundary.

Pressure buildup is affected more by the steam-water interface than by the drainage boundary. If the steam-water interface is not far from the wellbore, it will probably interfere with the straight line portion of the buildup. I think that is what is happening in the buildup presented in Fig. 2.

HEAT TRANSFER INTERFERES WITH DRAINAGE BOUNDARY EFFECTS

Under flowing conditions, the fluid temperature is less than the reservoir temperature. The resulting heat transfer causes temperature gradients in the rock. As the well is shut in, we have the phenomenon of temperature buildup in the rock along with the pressure buildup in the fluid. After some time, when the temperature and pressure have stabilized, the fluid in the wellbore boils. The boiling causes the temperature to drop, which, in turn will give rise to a new boiling cycle when the temperature has stabilized.

The pressure fluctuations caused by boiling interfere with the drainage boundary effects. This does not mean that the drainage boundary effects can be observed with certainty if the boiling did not occur. I think steam-water boundary effects will dominate any drainage boundary effects.

HOT-WATER BUILDUPS DIFFER FROM GAS/OIL BUILDUPS

There are significant differences between the buildups in hot-water and gas/oil wells. These are some of the differences:

1. Gas/oil systems generally are porous and have well-defined upper and lower boundaries. Most of the wells have complete penetration. On the other hand, hot water generally flows through fractures. Wells have partial penetration. We have two phases flowing near the wellbore and only single phase flowing some distance away from the wellbore. After shut-in, the two phases tend to become single phase all over.
2. In hot-water reservoirs, heat transfer interacts with the reservoir pressures and saturations. It is of no consequence in the oil/gas reservoirs.
3. Boiling tends to mask the boundary effects in hot-water wells.

FURTHER WORK IS NEEDED

We need to have an interpretative method for use in hot-water wells. Analytical solutions to the fluid and heat diffusivity equations are not likely to answer all the questions. We probably will need the help of a two-dimensional radius-height computer model to develop required information.

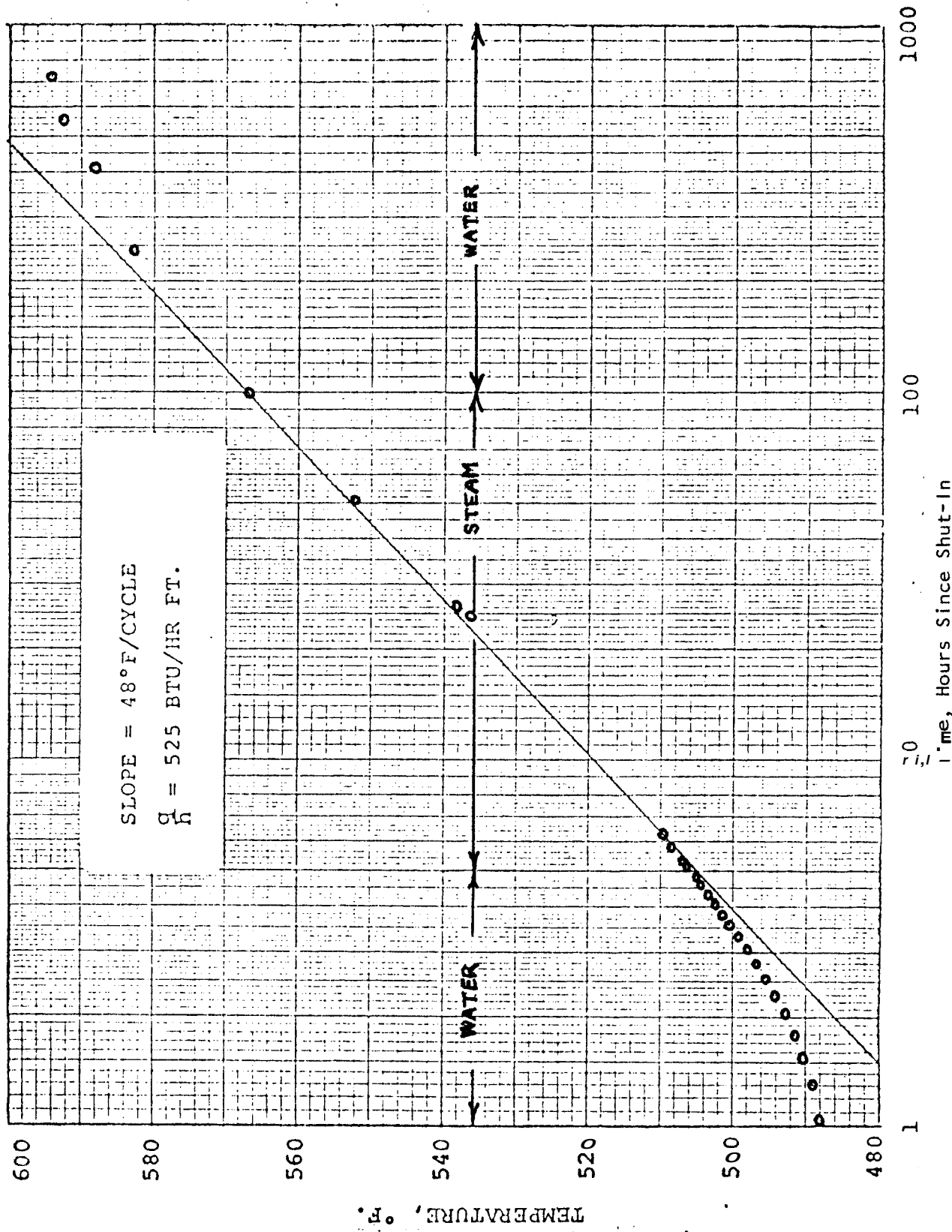


Figure 1 Temperature Build-Up in a Hot-Water Well.

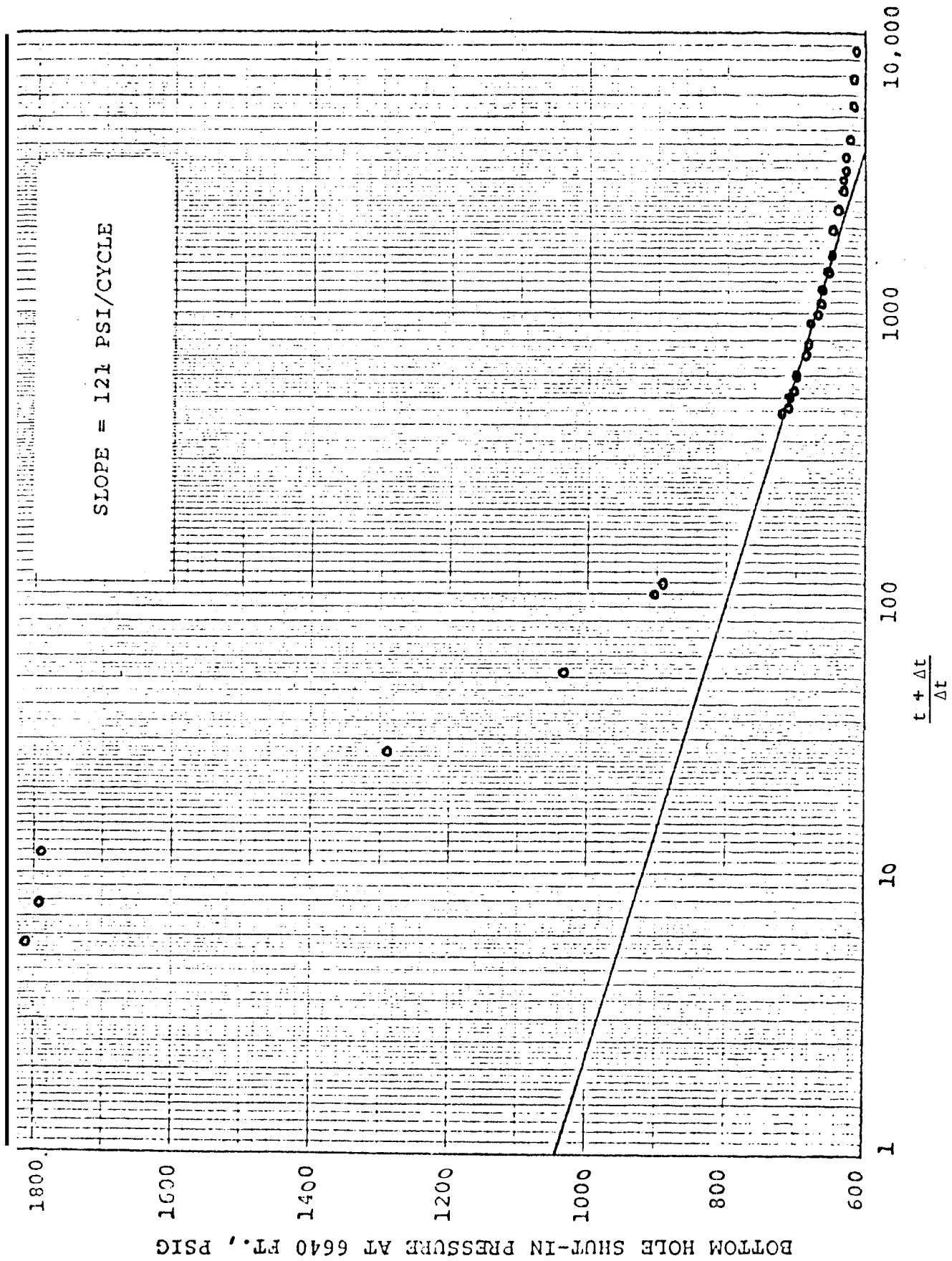


Figure 2 Pressure Buildup in a Hot-Water Well

WELL LOG ANALYSIS AND WELL TESTING
IN THE HEBER GEOTHERMAL FIELD

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Detailed studies of the reservoir performance and operating conditions of the Heber geothermal field have been completed. These studies indicate that a minimum development at the Heber site would be 200 MW utilizing a two-stage flash process. This paper summarizes part of the investigations which have occurred with attention given to log analysis and well performance.

Geology

Nine wells have been drilled to date. The deepest wells penetrate to 6,000 feet and have encountered alternating sand-shale sequences. Structural markers have not been encountered thus far. Representative core has been retrieved from seven to the nine wells drilled. Porosity from core analysis has been correlated with available density logs. The combination of core analysis and logs has permitted the assignment of both porosity and permeability to each foot of sand which was drilled.

Individual sand members had permeability changes between one and two orders of magnitude as sands were traced from well to well. A vertical layering approach was used to calculate an average permeability over 4,000 feet of section.

The log correlations showed that permeability deteriorated with depth (characteristic of increasing overburden), but that the reservoir still had favorable porosity and permeability at a depth of 6,000 feet.

Well Tests

A total of 19 drill stem tests, two 48-hour tests and three 90-day tests were conducted to evaluate reservoir performance. The drill stem tests were performed over a net sand interval which varied from 48 feet to 156 feet. All the drill stem tests are characterized by essentially instantaneous build-up after shut-in. Therefore, permeabilities could not be calculated by build-up analysis. From a qualitative standpoint, the rapid buildup to final pressure and low drawdowns suggest a reservoir of very high quality.

The two wells which were tested for 48 hours achieved high flow rates. The buildup was complete for both these wells within 45 seconds of shut-in and did not permit a calculation to be made.

Three wells were tested for a minimum of 90 days. Two of these wells were producers, with the third well operating as an injector for fluid from the two producers.

Injection well permeability was calculated from a falloff curve. A density log was not available for this well, so no comparison can be made. However, the composite layered geologic model gave close agreement to the falloff test over the same interval.

Two buildup tests were analyzed for one of the producers. Calculated permeabilities compared favorably with indicated permeabilities from density logs. Calculations on this well suggested significant wellbore damage.

Permeabilities determined using multiple rate tests on the third well were compared with log calculated values and steady state flow rate data.

The long-term pressure history of the three wells followed the pressure calculated theoretically by assuming an infinite aquifer with no influx at the outer boundary. It is possible that the real data might fit an aquifer of some finite size with a constant pressure boundary.

All the buildup data was characterized by a single straight line. This would suggest that boundaries were not encountered by the pressure transients and corroborates the producing pressure history.

The injection well was completed in a lower interval than the two producers. The producing and injecting wells (separated by one mile) were isolated from each other by continuous shales (conjecture). The long-term pressure history corroborates this picture as injection did not influence the producing well pressure. The two producers were completed in the same interval and were also one mile apart. The pressure history at the producers shows some minor slope variations which occur when rates are changed, but these are only qualitative indications of well interference. Rate changes were made frequently at both wells, and these tend to mask any interference effects which may have occurred.

During the well testing, wellhead temperatures were recorded. For all flow rates which were encountered at the producing wells, flow was single phase water from approximately 3,000 feet deep. It was observed that wellhead temperatures approached equilibrium very quickly. At flow rates between 5,000 and 10,000 B/D, wellhead temperatures were within 7°F of the average bottom hole temperature after only 7 days. At flow rates above 15,000 B/D, surface temperatures were only 2°F below bottom hole conditions after 5 days, and 1°F after 25 days. It can be concluded that heat loss in the wellbore in single phase flow will be negligible during actual production operations. Geothermal well production rates are expected to be generally in excess of 30,000 B/D.

Conclusion

The geology and information gained from well testing was used as the foundation for a reservoir simulation to predict reservoir performance. The rationalization of information gained from these two sources plays a very important role in giving reliability to performance predictions. In the case of the Heber field, the log data, core data and well test data correlate satisfactorily. The reservoir performance prediction of 200 MW is therefore realistic.

The observation of negligible heat loss in the wellbore during normal production operations in water systems is significant. Wells may be directionally drilled such that a larger percentage of the total flow path is covered in the wellbore, rather than in surface flow lines.

It is worth noting that the overall analysis used for this geothermal reservoir was similar in nature to that used to predict oil reservoir response. The data gathering procedure, analysis and overall method of approach used for many years in evaluating oil reservoirs have direct applicability to geothermal reservoirs.

GEOTHERMAL WELL TESTING AT
ROOSEVELT KGRA, BEAVER COUNTY, UTAH

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This paper describes testing procedures used by Phillips Petroleum Company at the Roosevelt KGRA prospect. The equipment and techniques described herein are not all original or new ideas but represent a combination of elements chosen after an intensive review of the state of the art. Special acknowledgment should be given to Jerry Jones of Union Oil Company and Dick Bolton of the New Zealand Ministry of Works for their cooperation and advice.

During the spring of 1975, Phillips Petroleum engaged Loffland Brothers to drill several geothermal exploration wells on the Roosevelt KGRA prospect in Beaver County, Utah. In May we encountered geothermal hot water in our KGRA 3-1 well. A three-hour flow from this well through an open pipe indicated flows in excess of 600,000 pounds per hour of fluid at wellhead pressures approaching 400 psig. The flow was measured using the technique described by Russell James for measuring flow discharging at the speed of sound to the atmosphere.¹ Concern about the accuracy of this type of measurement (flow conditions are well outside the limits described by James) and the prudence of continued testing with our crude testing facilities led us to seek a safer and more accurate means of flow testing the well.

After reviewing the technology available for measuring two-phase steam/water flow, it was decided that the most accurate method would probably be to separate the steam and water phases and measure them separately. A survey of current practice revealed that the Bottom Outlet Cyclone was the most popular design in current use, and for that reason we chose to use it: for our geothermal testing. Conversations with Dick Bolton of the Ministry of Works and Development, New Zealand, led us to a paper by P. Bangma on the development and performance of a steam-water separator for use on geothermal bores. In it he detailed the development of the steam separator used at Wairakei which incorporates a spiral inlet (as opposed to a tangential inlet) to permit a substantial increase in inlet velocity without a corresponding increase in liquid carried over into the steam phase. Our discussions with Dick Bolton led us to believe that the spiral entry would indeed permit us to nearly double the inlet velocity allowable in the conventional tangential design. As a result of this research we settled on the following design parameters:

Maximum working pressure	550 psig
Design steam flow @ 200 psig	200,000 #/hr.
Design water flow @ 200 psig	800,000 #/hr.
Design temperature	600°F

These parameters result in a 154 ft/sec superficial inlet velocity for a 36" I.D. separator with a 12" diameter inlet. (Superficial inlet velocity is the

¹Measurement of Steam-Water Mixtures Discharging at the Speed of Sound to the Atmosphere, Russell James, New Zealand Engineering, 21(10):437-31 (Oct. 1966).

velocity calculated considering only the vapor phase in the inlet mixture.) It is important to remember when selecting a separator that increasing flow rates and decreasing flowing pressure each increase the required separator size, i.e., while the vessel must be designed for the maximum expected working pressure it must be sized for the minimum expected flowing pressure. The separator, fabricated by WKM-Brewster, includes an integral water drum separated internally from the separator section. The drum was included to try to minimize flashing of water in the water metering line.

The piping scheme shown for the well testing facility (Figs. 1 & 2) was designed to be simple to erect, able to accommodate anticipated thermal expansion safely, and resistant to erosion at the pipe turns. To accommodate thermal expansion, the system is designed to include a large horizontal loop supported in the vertical direction and free to move in the horizontal plane. In addition, the separator base is free to slide and a WKM-Brewster internal expanding wellhead is used to absorb the expansion of the wellbore casing.

After the initial operation of the facility we added several guy wires to support the vessel and piping. These restraints are kept slack until the system is hot and are then tightened enough to snub any vibration which may occur in the course of operation. Even with the special wellhead design, the wellhead rose about 4 inches when the well got hot and in the initial test appeared to place an undesirable strain on the piping. The use of a one and one-half ton hydraulic jack under the first pipe support off the wellhead appeared to alleviate the problem. As a safety precaution, this was verified by pipe stress calculations using piping displacements actually measured during initial tests. These calculations show that the use of a hydraulic support can provide a safe, inexpensive and reliable means of compensating for pipe displacement due to expansion. Selecting an appropriate size jack for the job allows an operator to support the piping during well tests with a controlled amount of thrust and little fear of overcompensating for thermal expansion.

In spite of our satisfactory operation of this facility as designed, operators considering testing wells at rates in excess of one million pounds per hour would be well advised to consider rigidly anchoring all major pieces of the facility and using some form of expansion joint. Barco Division of Aeroquip Corporation has a series of ball-type joints for steam service that might be suited for this type of service. All changes of direction in the piping except those immediately upstream of the separator and the meter runs are accomplished using tees with the run end enclosed with a plate. This provides a hydraulic cushion at each turn and it is believed that this will minimize the erosion normally associated with elbows used in this type of system.

System Controls

The system is controlled by regulating the pressure with a pressure control valve on the steam line and by regulating the level in the separator with a level control operating a diaphragm-actuated valve in the water line. In sizing the water control valve, one has to be careful to size the valve for flashing liquid across the valve. In our application, the use of an 8" Fisher type 657ED with an equal percentage, 3" travel cage has provided very satisfactory service and appears to offer a reasonable margin for capacity in excess of design.

Flow Measurement

The facility includes equipment to measure pressures and temperatures at the wellhead, the steam meter line and the water meter line. In addition, pressures are measured at the separator and downstream of the steam and water control valves (measure back pressure of muffler). Steam and water flows are measured using standard orifice plates in the meter runs and recorded on American Meter Recorders. The quality of the separated steam is measured using a throttling calorimeter as described in the ASME Power Test Code PTC 19:11-1940. Connections for taking samples are provided at the wellhead for total flow and downstream from the separator for the separated steam and water.

Flow Discharge

Steam and water in the system are discharged to a pit through the muffler shown in Fig. 3. Design is based upon mufflers used by Union Oil at Valles Caldera and does an excellent job of silencing and dissipating the flow. The total open area of the slots is approximately four times the area of the pipes feeding it. It is especially important to place the slots on the sides of the pipe only and to arrange them so that the thrusts are balanced during use.

Facility Operations

In operation thus far, the facility has provided us with accurate measurements and reliable service. One area which is still not providing us with totally satisfactory information, however, is the measurement of water flow. The small pressure drop experienced between the separator and the meter and the pressure drop across the meter is sufficient to cause flashing of small amounts of water into steam in the system. This flashing causes a 10 to 20 percent error in the separated water measurement. At the present time we are producing with a relatively constant enthalpy up the wellbore so an accurate calculation of the total flow can be made from our separated steam flow measurement. In the future, however, it may become necessary to lower the elevation of the water meter piping relative to the separator to eliminate this flashing. In tests run to date the facility has provided satisfactory operation over the following range of conditions:

Wellhead pressure	385 psig	294 psig
Pressure drop wellhead to separator outlet	20 psi	35 psi
Total flow rate	720,000 #/hr	925,000 #/hr
Separated steam quality	100%	99%
Muffler back pressure	25 psi	

Measuring Reservoir Pressure

All flow testing using this facility has been performed on Well 54-3 in the Roosevelt KGRA prospect. This well was drilled adjacent to the 3-1 well when 3-1 was judged to be unsuitable for flow testing due to casing problems. KGRA 3-1 was used as an observation well for these flow tests and provided us with information concerning the reservoir. This well was instrumented with a Sperry-Sun Permagauging recording system. The Permagauging surface recorder was

connected to a downhole system consisting of a Permagaugge concentric expandable chamber suspended to the well bottom by a .020" I.D x .094" OD stainless steel capillary tube. This tube and chamber were filled with nitrogen and the Permagaugge recorder measures the surface pressure of this column and calculates the corresponding bottom hole (reservoir) pressure. This test resulted in agreement between a wellhead monitor and the recorder tied to the downhole system within a range of less than .2 psi. The data we were able to gather using this system were of excellent quality and provided plots for the various solutions of reservoir calculations which required virtually no adjustments to the measured data. The system is capable of providing the quality of data needed to perform accurate reservoir calculations but not without some difficulties:

1. The elements of the system are not entirely reliable. Leaks in the gas column and calibration problems brought on by the harsh environment are the major factors causing unreliable operation.
2. The system requires extensive attention prior to, during and after the test to provide continuous operation.
3. Some means of protecting the surface elements of the system from the environment must be provided.
4. The system requires an external power source to sustain operation during the measuring period.

In conclusion, the facility used by Phillips at the Roosevelt KGRA has demonstrated the capability of providing accurate data in a safe fashion in the testing done to date. Further testing will no doubt result in refinement of the equipment and methods used. The most important single factor to be considered in designing and operating such a facility must be the safety of the people involved in the testing. Every effort should be made to insure the integrity and safety of the system.

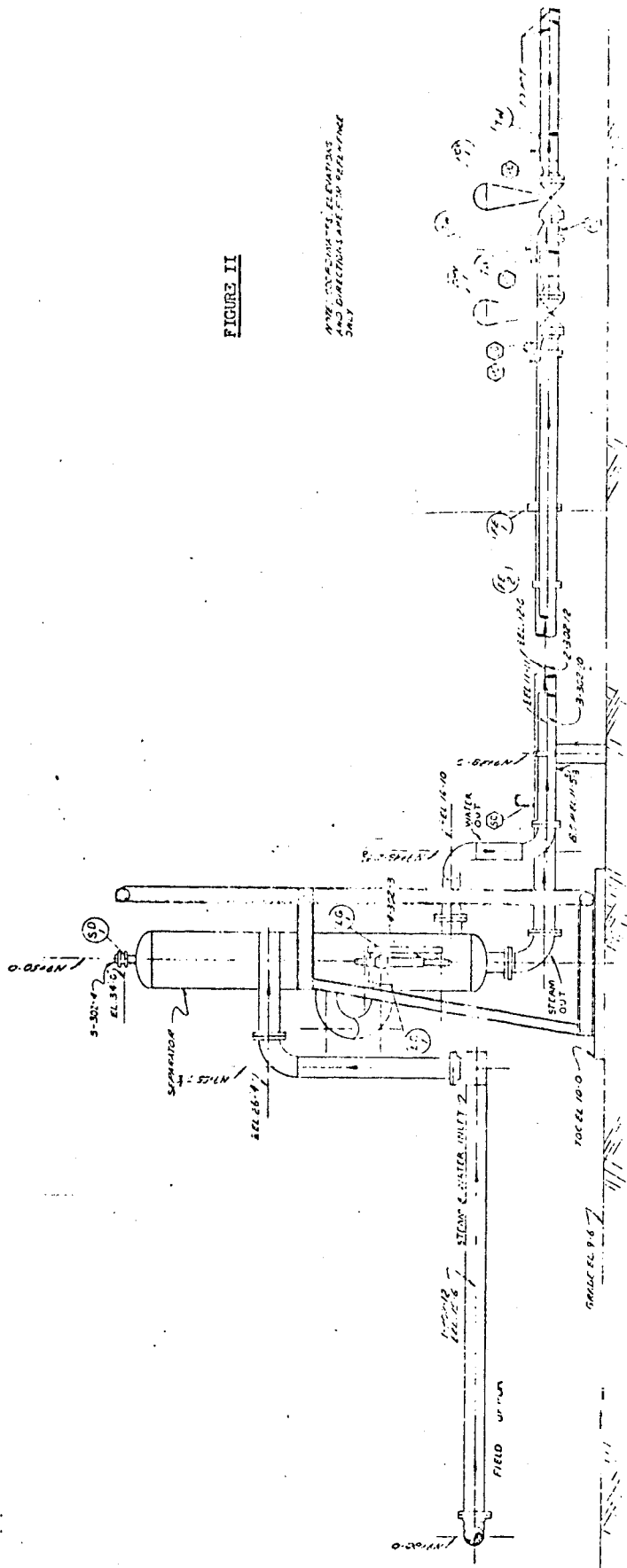
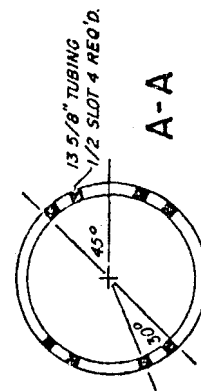
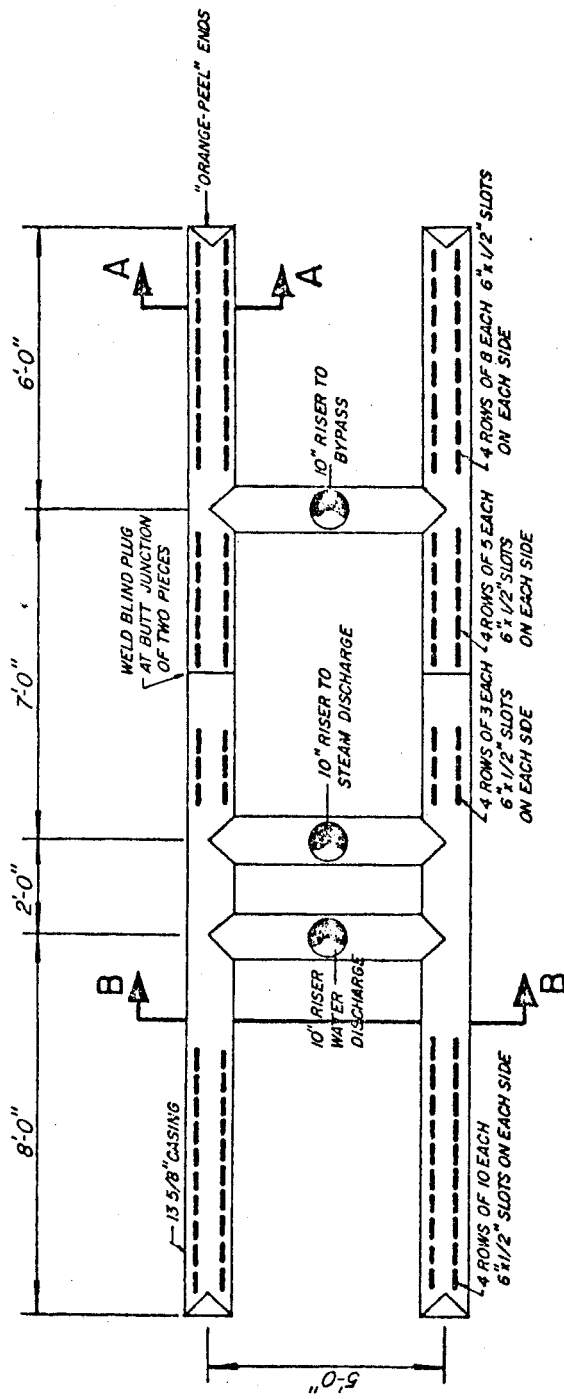


FIGURE II

NOTE: SEE FIGURES, ELEVATIONS
AND DIRECTIONS FOR REFERENCE
ONLY

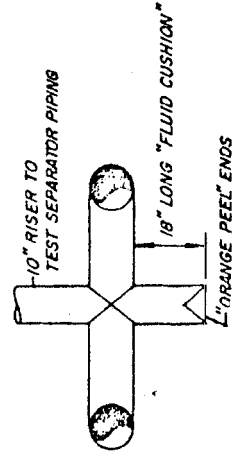
PHILIPPS PETROLEUM COMPANY
BAYLOR, TEXAS

THIS IS A
REDUCED
PRINT



NOTE 1: ALL SLOTS MUST BE ON SIDES OF PIPE AS SHOWN AND EACH SLOT MUST HAVE A CORRESPONDING SLOT ON THE OPPOSITE SIDE OF THE PIPE. NO SLOTS ON THE TOP OR BOTTOM QUARTER OF THE PIPE.

NOTE 2: FABRICATE FROM 13 5/8" CASING.



EACH RISER TO HAVE AN 18" FLUID CUSHION BELOW IT.

DIFFUSER ASSEMBLY

FIGURE III

SHELL'S ACTIVITY IN THE GEYSERS AREA

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Houston, Texas 77001

Shell has drilled one dry hole and one commercial discovery in The Geysers area of northern California. The dry hole was hot ($\pm 447^{\circ}\text{F}$) but failed to encounter fractures necessary for commercial steam recovery. The discovery producer, located one and one-half miles south of The Geysers field, encountered dry steam flowing at rates of about 200,000 lb/hr. A confirmation well is currently being drilled.

Temperature gradients range from 2-4 $^{\circ}\text{F}/100$ ft. above 3,000 ft. and from 6-8 $^{\circ}\text{F}/100$ ft. from 3,000 ft. to the steam reservoir. The reservoir temperature ($\pm 465^{\circ}\text{F}$) and pressure (± 500 psia) are typical of The Geysers area. Local concentrations of hydrogen sulfide in excess of 3,000 ppm were encountered in one well.

Shell started acquiring acreage in 1971, and now holds 15,000 acres (Fig. 1). Two Federal leases, U.S. One (2477 acres) and U.S. Two (1600 acres) were acquired in January 1974 in the first Federal geothermal competitive lease sale.

U.S. Geothermal Two-1 was drilled to explore for fractured reservoir conditions in the objective Franciscan graywacke interval below serpentine sealing rocks. Two serpentine beds were encountered at depths of 2,300 ft. and 4,000 ft. in the original hole. Graywacke and interbedded volcanic rocks were penetrated below these beds. Several steam shows were noted below 4,000 ft. and a static temperature of 325 $^{\circ}\text{F}$ was calculated from a wire line survey at 4,070 ft. However, stuck pipe forced abandonment of the hole at a true vertical depth of 6770 ft.*

The well was then redrilled from 2,770 ft. to 8125 ft. Several non-commercial steam shows were encountered in the redrilled hole below a serpentine bed at 4170 ft. A wire line survey indicated a formation temperature of 447 $^{\circ}\text{F}$ at 6,150 ft. (Fig. 2). The average static temperature gradient in the interval from 3,000 ft. to 6,150 ft. is 5.8 $^{\circ}\text{F}/100$ ft. The well was plugged, and abandoned at 8120 ft. and no temperatures were obtained below 6,150 ft. Geologic and temperature conditions encountered in this hole indicate commercial steam reserves should be present on this U.S. Geothermal leasehold.

Our discovery well, U.S. Geothermal One-1, spudded in June 1975 and encountered commercial steam on July 10, 1975, at 4920 ft. in the fractured Franciscan graywacke (Fig. 3). Bad hole conditions prevented our obtaining static temperature data from the well. However, nine separate readings were taken with maximum reading thermometers. This data shows a gradient of about 8.1 $^{\circ}\text{F}/100$ ft. in the interval from 3000 ft. to 3870 ft. (Fig. 2). This well has a low geothermal gradient (2.3 $^{\circ}/100$ ft.) above 3000 feet which may be the results of shallow groundwater movement.

*All depths are true vertical depths.

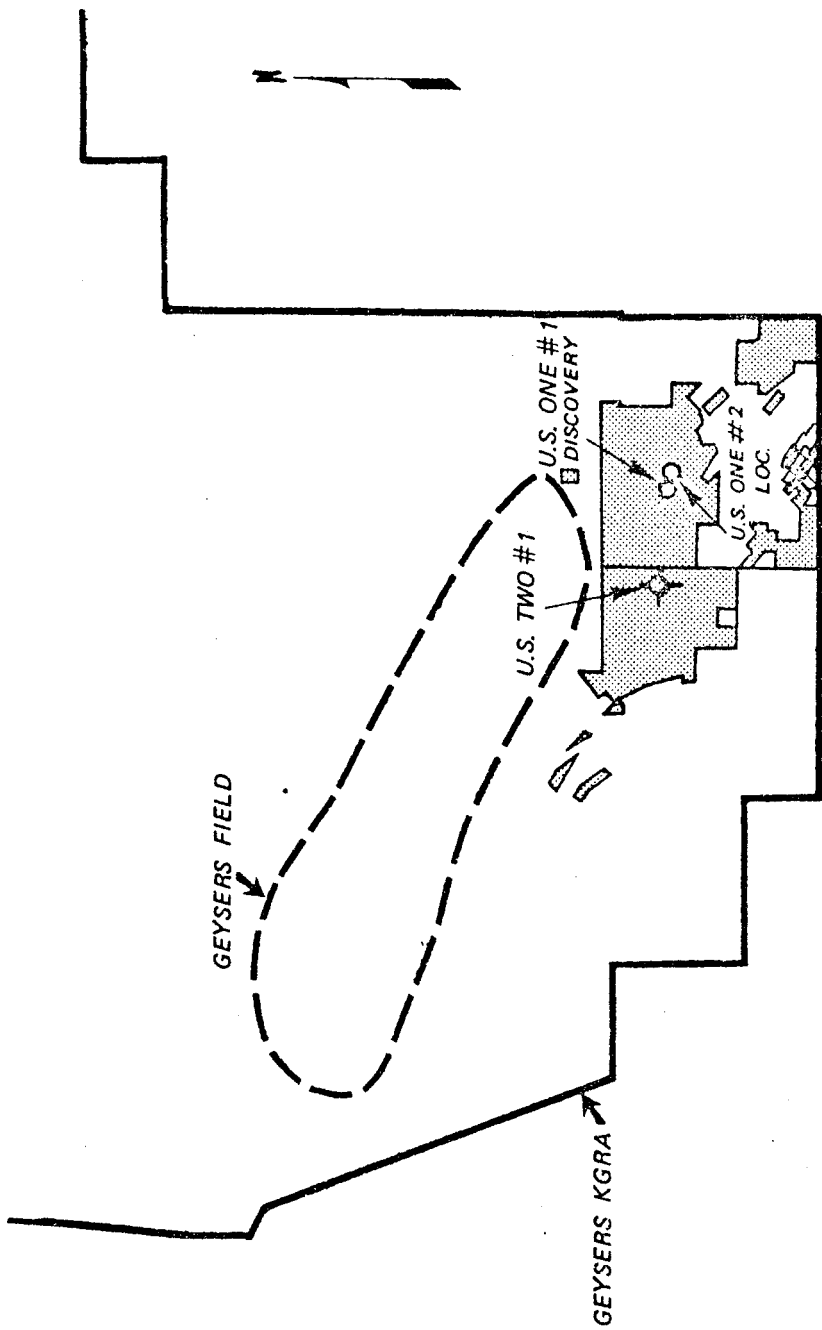
Shell-U.S. Geothermal One-1 was flow tested using three different orifice plates. Average flow data are as follows:

<u>Orifice Size</u> (in.)	<u>Pressure</u> (psia)	<u>Temperature</u> (°F)	<u>Rate</u> <u>MLB/HR</u>	<u>Quality</u>
6	149	353	183	.96
7 1/2	96	320	191	.99
8 3/4	75	306	195	1.00

Flow test and calorimeter data indicate the well has an absolute open flow potential of approximately 200,000 lbs/hr dry steam. However, the range of orifice plate sizes was too narrow to accurately determine the maximum rate or AOF coefficient and exponent. A flow stream sample had the following composition:

<u>Constituent Gas</u>	<u>Mole</u> <u>Per Cent</u>	<u>PARTIAL GEOCHEMICAL ANALYSIS (Water)</u>	
Hydrogen	2.292	Sulfate, mg/l	10
Nitrogen	9.712	Chloride, mg/l	14
Oxygen	0.012	Bicarbonate, mg/l	88
Carbon Dioxide	48.783	Borate, mg/l	26
Hydrogen Sulfide	0.000	Organic Acids, mg/l	110
Carbon Monoxide	0.000		
Oxides of Nitrogen	0.000	Specific Gravity 1.003 @ 60°F.	
Methane	28.598	Resistivity 5,150 Ohm Cm @ 75°F.	
Ethane	0.020	pH Value	7.20
Benzene	0.015		
Toluene	0.017		
Xylene	0.008		
Water	10.543		

Our confirmation well, Shell-U.S. Geothermal One-2 was spudded 7/31/75 and drilled to 7680 ft. The temperature gradient (Fig. 2) in this well was 3.8°F/100 ft. above 3000 ft. and 8.1°F/100 ft. in the interval from 3000 ft. to 4490 ft. A small steam flow of 50,000 lbs/hr was encountered at a depth of 6780 ft. The flow stream contained approximately 80 ppm hydrogen sulfide. This bore was plugged back from 7680 ft. and sidetracked from 4560 ft. Another small steam flow of 12,000 lbs/hr. was encountered in the redrill at 4840 ft. Hydrogen sulfide content exceeded 3000 ppm so the redrill borehole was plugged at 5250 ft. and a second redrill commenced at 2080 ft. We are currently drilling below 6000 ft.



- LEGEND -



SH LL U.S. LEASING UNITS

- ⊕ 1974 DRY HOLE
- 1975 PROGRAM

GEYSERS GEOTHERMAL PROJECT

ZW-66

FIGURE 1

TEMPERATURE TRAVERSES SHELL - U.S. GEOTHERMAL LEASES

DEPTH (FT.) VS. TEMPERATURE (°F)

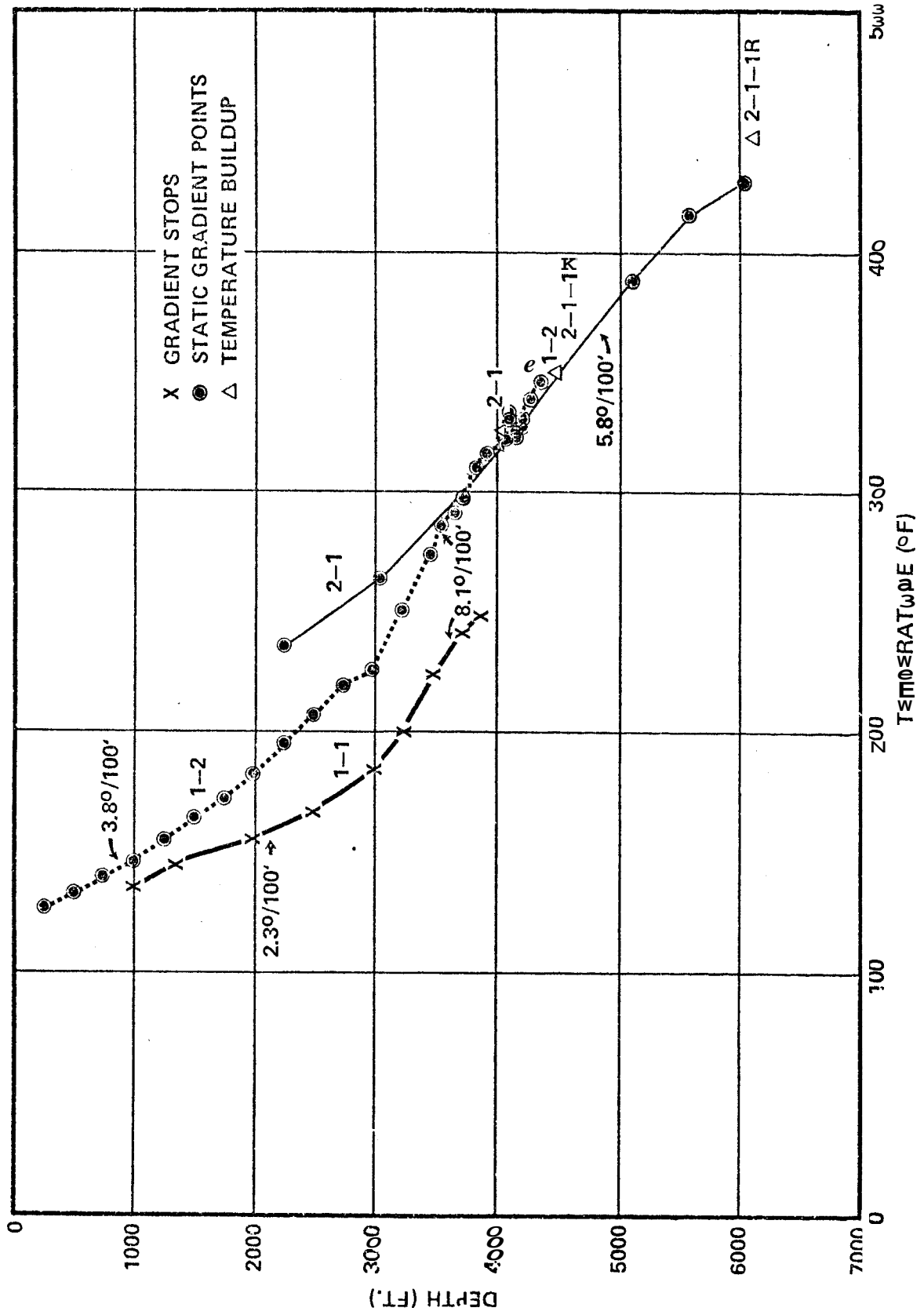
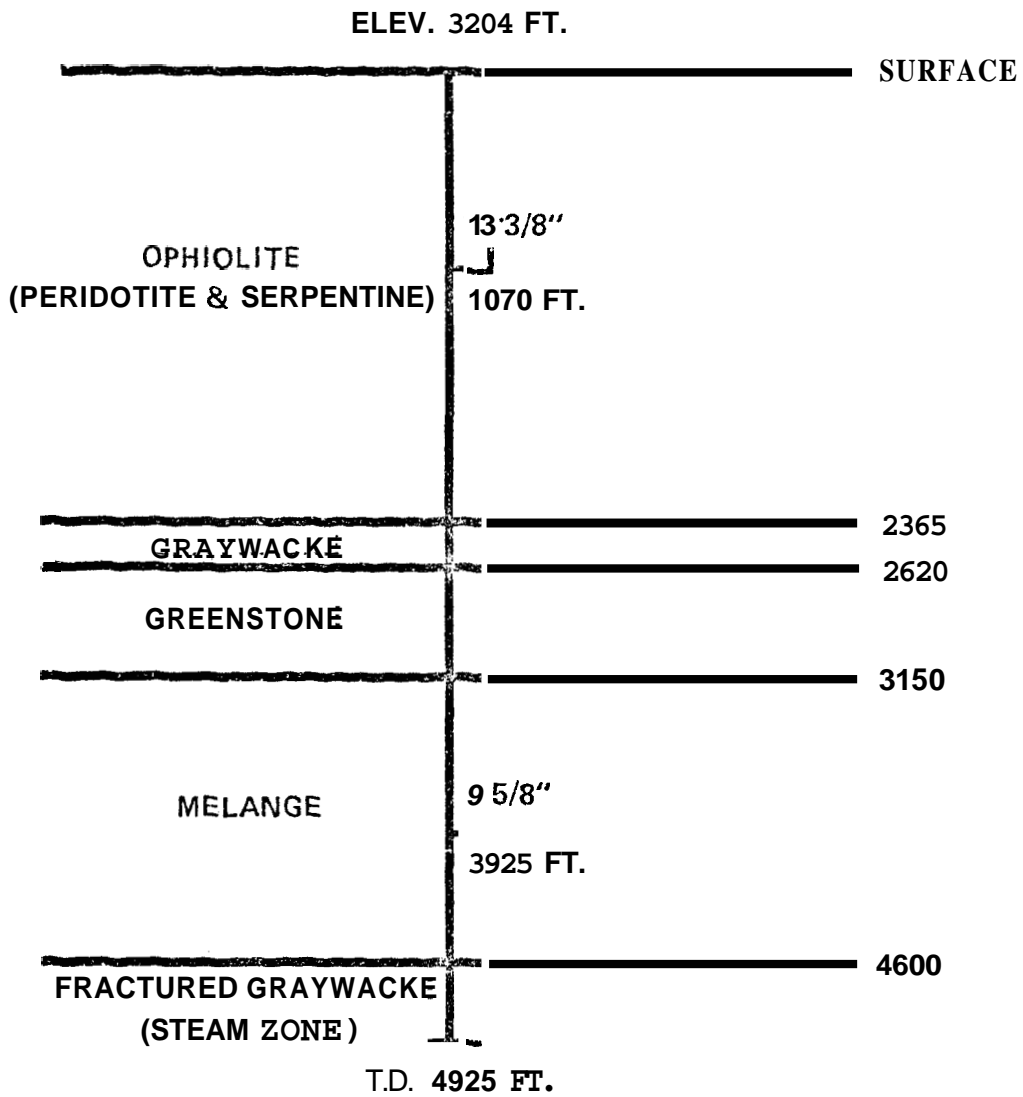


FIGURE 2

SHELL OIL COMPANY
U.S. GEOTHERMAL ONE # 1



SEQUENCE OF ROCK TYPES

WATER ENTRY BELOW STEAM PRODUCTION:
A CASE HISTORY AT THE GEYSERS

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Burmah Oil and Gas Company has drilled over twenty holes in the south-east portion of The Geysers steam field; to date only one has proved non-productive. This report documents a case history unique to Burmah of a water entry below steam production.

History

A 12-1/4" hole was drilled to 3000' and 9-5/8" OD casing was cemented to the surface. Burmah then directionally drilled an 8-3/4" hole with air and encountered minor steam entries at 5120', 6335', and 6457', as shown on Fig. 1. No additional steam entries were found below these depths. Total steam flow measured less than 20,000 pounds per hour.

At 7580' an increase of air pressure on the stand pipe from 420 psig to 580 psig was noted. The well started making 128 barrels per hour of water having a temperature of 188-190°F measured at the surface. The partial chemical analysis of this water is listed on Fig. 2, Column 1. Air drilling continued to 7665' with no decrease in water production. Drill pipe was pulled out of the hole to 4363' and air circulated for four hours. The well produced only steam, no water. No temperature or pressure survey was run. The lack of water at 4363' indicates a water pressure of less than 1355 psig.

Since the hole produced a sub-commercial rate of steam, Burmah decided to plug the hole and directionally redrill the hole in a more westerly location. Steam entries were encountered at 4259', 4362', 5480', 5660', 5943', 6731', 6858', and 6980'. Fig. 1 shows the location of these steam entries. The hole produced approximately 120,000 pounds of steam per hour after the last steam entry. Again the hole produced water, but at a lower rate of approximately 80 barrels an hour. The analysis of this water is shown on Column 2 on Fig. 2. The water entry indicated by the increase of standpipe air pressure was at 7138'. No pressure or temperature survey was run. The hole was plugged with 43 sacks of cement. The drill pipe stuck while pulling out of the hole. The best estimate of the top of the plug is 6830' measured by the free point indicator on the stuck pipe. The stuck drill pipe was partially recovered to 6062'. Further recovery attempts proved unsuccessful.

After the drilling rig was released, the surface well head pressure stabilized at 484 psig. A static pressure and temperature survey stopped at 3515'. The survey indicated essentially saturated steam. At a later date the well, when first opened for a flow test, produced water along with steam. Column 3 of Fig. 2 lists the partial chemical analysis. Subsequent flows at higher rates produced saturated steam with no entrained water. The isochronal testing indicated a flow rate of 86,000 pounds of steam per hour. An analysis of the steam condensate produced at this flow rate is shown in Column 4 of Fig. 2.

Discussion

The chemical analyses of the two water entries are similar but not identical even given allowances for sampling and testing errors. The samples are dissimilar enough to preclude the positive conclusion that they are the same water. It is plausible that the two waters, though sharing a common origin, are located in separate fracture systems. Both water entries are in silicious argillites.

The water produced on the first test (Column 3) indicates contamination from cement (pH and chloride) and also some evaporation of the deep water as inferred from the increased boron concentration. The analysis of the steam condensate is typical of steam condensate analyses of wells in the surrounding area. A physical chemistry analysis has not been attempted to determine if the chemical constituents of the water and steam are in equilibria.

A review of the wells in the surrounding area shows this well to be bounded by commercial production 2100' to the north, 4000' to the west, 1100' to the south and 3700' to the east. None of these wells showed any indication of deep water entries. It should be noted, however, that none of these wells reached the equivalent vertical depth of the water entries in the original hole or redrill of the subject well. Other wells at greater distances always have been drilled to at least 700 vertical feet below the deepest water entry. The vertical and horizontal difference between the two water entries of 407' and 540', respectively, indicates a possible structural rather than an hydrological control of the water in this localized area. Because temperature and pressure surveys were not conducted while the holes were producing water, conclusions about steam-water communication and equilibrium are difficult.

Due to the physical condition of the hole (apparent sharp dog leg and pipe left in the hole), it is not possible to positively demonstrate by temperature and pressure surveys that the water has been shut off by the cement plug. However, it is certainly inferred indirectly by the quality of the steam produced during the well test. The loss of steam flow rate indicates also that at least the bottom two steam entries were effectively plugged.

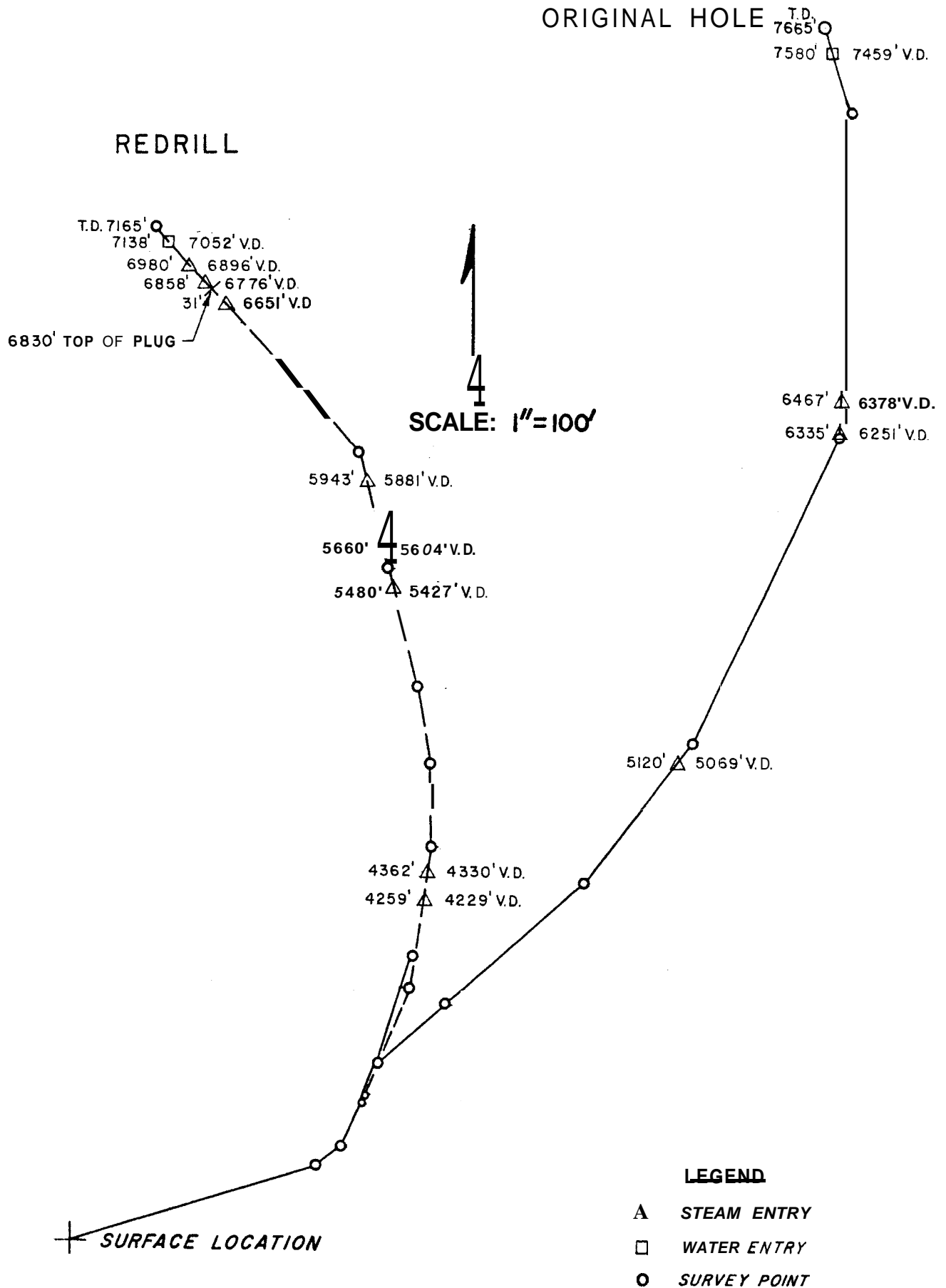


FIGURE 1

CHEMICAL ANALYSES

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
pH	5.3	5.1	8.4	5.7
Specific Conductance µmhos/cm @ 25°C	650.0	1000.0		
Calcium, mg/l	<10.0	10.0		< .1
Magnesium, mg/l		37.0		.005
Ammonia, mg/l		43.1		25.2
Sodium, mg/l	146.0	117.0		< .1
Iron, mg/l				1.0
Boron, mg/l	82.8	24.1	142.0	2.4
Potassium, mg/l	110.0	86.0		< .01
Aluminum, mg/l		< .02		c. 1
Mercury, µg/l		54.0	1.5	2.4
Sulfate, mg/l		414.0		10.0
Chloride, mg/l	41.0	10.0	26.0	2.0
Fluoride, mg/l		8.0		< .01
Bicarbonate, mg/l		12.2		80.0
Nitrate, mg/l		2.2		15.5
Silica, mg/l		400.0		1.2
Sulfide, mg/l				100.0

1. Water entry of original hole.
2. Water entry of redrill.
3. Water produced on initial well flow.
4. Steam condensate at 85,000 pounds per hour flow rate.

FIGURE 2

AN INTERFERENCE TEST IN ALFINA GEOTHERMAL FIELD
(NORTHERN LATIUM, ITALY)

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A fina field is situated in central Italy near the Lake of Bolsena.¹ Its geo logical-stratigraphical sequence is as follows:

- a. A thick (>500 m) Cretaceous-Eocene sedimentary series in flysch facies comprising mainly clays and marls. This flysch series forms the cap rock;
- b. A Mesozoic sedimentary series, stratigraphically quite regular, of more than 400 m thickness, comprising mainly carbonates (limestones, marly limestones and calcarenites). This series forms the geothermal aquifer, having a high permeability as a result of the presence of fractured zones.

Fig. 1 shows the location of the wells. Fig. 2 gives a cross-section of the reservoir along the A-A line shown in Fig. 1, using the geological data from wells 13, 1 BIS, 2 and 4 which lie almost on a straight line on the cross-section.

The field produces CO₂ in the highest part of the reservoir (wells ALF 1, ALF 1 BIS, ALF 13) while it produces water where the cap rock is lower (wells ALF2, ALF 4, ALF 5--Fig. 3). This fact, together with the various pressure and level measurement from all the wells, which will be discussed later, have led to the schematic cross-section shown in Fig. 2 a gas cap lying over a water-table.

The temperatures found in the formations have a gradient of about 0.2°C/m in the cap rock down to the top of the reservoir; for about 400 m below that, the temperature increases slowly from 130 to 150°C.

ALF 1 BIS well produced CO₂ from the time of its explosion on 20 May 1974 to 8 September 1974 when it began carrying water. During this period the well was shut-in on various occasions to check the pressure behavior in the reservoir. At the same time the water level was recorded in ALF 2 well, which, although sterile, is in contact with the reservoir.

Pressure and Water Level Analysis

The graph shown in Fig. 4 gives the water-level versus time for ALF 2. We can see that each single production phase causes the level to decrease. The constant level seen in the control well (ALF 2) at the end of each production phase indicates that the system may be considered as a closed one at least for periods of some years. If a graph is drawn of the level decrease as a function of the quantity produced (Fig. 5), then a proportional relationship appears.

By utilizing the pressure data in the gas cap and at a given depth beneath the water table in static conditions we can determine the location of the gas-water interface. It is initially 120 ± 5 m from the reservoir top.

The system is made up of water, rock and CO_2 in the gas phase and dissolved in water.

During production ALF 1 BIS produces gas, the gas and water pressures decrease, part of the CO_2 dissolved in water passes into the gas phase, the gas, water and rock expand as a consequence of the pressure decrease and the gas-water interface rises.

The rise in the interface was deduced from the fact that the gas pressure decrease was greater than that of the water.

At this point we might consider the variations in volume of the system as a result of the pressure decreases which, in their turn, are a result of the gas extraction.

The volume of gas extracted in average reservoir conditions can be expressed as

$$V_e = -\Delta p_w V_w (c_w + c_f) - \Delta p_g V_g (c_g + c_f) - \Delta p_g V_w A \quad (1)$$

where c_w , c_f and c_g are the compressibility values of water, rock and gas respectively (atm^{-1}).

V_w and V_g are the volumes in reservoir conditions for the water and gas contents of our system (m^3).

V_e is the gas volume extracted in reservoir conditions (m^3).

Δp_w , Δp_g are the pressure variations of the liquid and gas phases (atm).
 A is the volume of the gas dissolved in water per unit of water volume (both in reservoir conditions) for a unit pressure rise ($\text{atm}^{-1} \frac{\text{m}^3 \text{CO}_2}{\text{m}^3 \text{H}_2\text{O}}$).

Introducing the experimental values equation 1 becomes

$$a V_w + b V_g = V_e \quad (2)$$

where both V_w and V_g are the unknown quantities.

We can find only a range of variations for the unknown gas and water volumes.

The maximum value for V_w is obtained for $V_g = 0$.

$$V_w < \frac{1}{a} V_e$$

The maximum gas value can be estimated letting $V_w = 0$.

$$V_g < \frac{1}{b} V_e$$

The drilling data for ALF 2 well and an estimation of the area permeated by water and gas have led us to suppose that

$$V_w \geq 6 V_g \text{ and from (2) } V_w \geq \frac{6}{6a+b} V_e, \quad V_g \leq \frac{1}{6a+b} V_e$$

Combining all the preceding inequalities we can define a possible range for V_w and V_g as:

$$\frac{6}{6a+b} V_e \leq V_w \leq \frac{1}{a} V_e \quad 0 < V_g \leq \frac{1}{6a+b} V_e$$

The ratio between minimum and maximum values obtained for V_w is less than 2.

Transient Analysis

The level transients in ALF 2 caused by two production periods from ALF 1 B18 were studied.

First of all, it must be noted that the common transient analysis assumptions were not valid.

1. Our reservoir is not homogeneous nor isotropic but fractured with an unknown permeability and porosity distribution.
2. Two completely separate phases are present: one phase is produced, but the pressure is controlled in the other. Reservoir compressibility and viscosity are unknown factors.
3. The producing well does not penetrate the reservoir and the flow pattern is almost certainly not radial.
4. The bottom and lateral boundaries are not known.

However, we tried transient analysis methods for homogeneous, isotropic medium and single phase fluid² as a first step and we hope that further discussion will help us to find more appropriate models.

A first glance shows that an early transient period was followed by typical pseudo steady-state.

The line source solution seems appropriate in the early period (≈ 50 hours) while the pseudo steady-state conditions are apparent after 100 hours, showing evidence of a closed boundary.

Dimensionless pressure p_D versus dimensionless time t_{DA} were generated for a rectangular reservoir with impermeable walls.

A good match (Fig. 6) was obtained for the rectangle shown in the map (Fig. 7) for the first production period.

The data for the second production period are not in agreement with those from the first period. Therefore a good match is not possible with the same type curve.

A rise in the water table may be responsible for this discrepancy. The matchpoint gives the following values:

$$\frac{k}{\phi \mu c} = 0.7 \text{ m}^2/\text{sec}$$

$$\frac{hk}{\mu} = 3500 \text{ darcy-meter/cp}$$

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Nomenclature

- A = volume of the gas dissolved in water per unit of water volume both in reservoir conditions) for a unit gas pressure rise (atm^{-1})
- a = dimensionless constant
- b = dimensionless constant
- c = compressibility (atm^{-1})
- c_f = effective compressibility of the formation. Relative change in pore volume per unit change in pressure (atm^{-1})
- c_g = gas compressibility (atm^{-1})
- c_w = water compressibility (atm^{-1})
- h = formation thickness (m)
- k = permeability (darcy)
- p_D = dimensionless pressure drop
- Δp_g = change in gas pressure due to gas extraction (atm)
- Δp_w = change in water pressure at a certain depth due to gas extraction (atm)
- t_{DA} = area-based dimensionless time
- V_e = gas volume extracted measured in reservoir conditions (m^3)
- V_g = gas volume in the reservoir (m^3) in reservoir conditions
- V_w = water volume in the reservoir (m^3) in reservoir conditions
- ϕ = porosity
- μ = viscosity (cp)

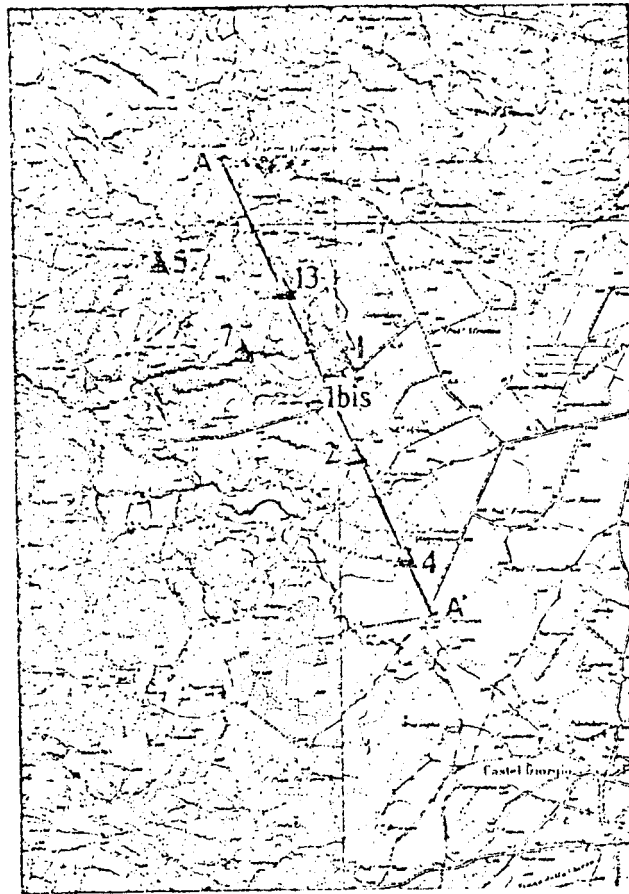


Fig. 1 - LOCATION OF THE WELLS IN ALFINA REGION

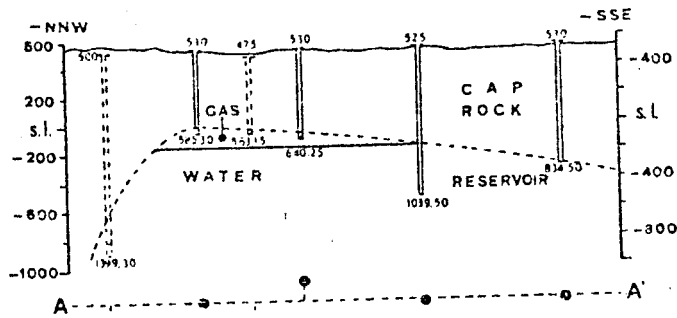


Fig. 2 - GEOLOGICAL CROSS SECTION

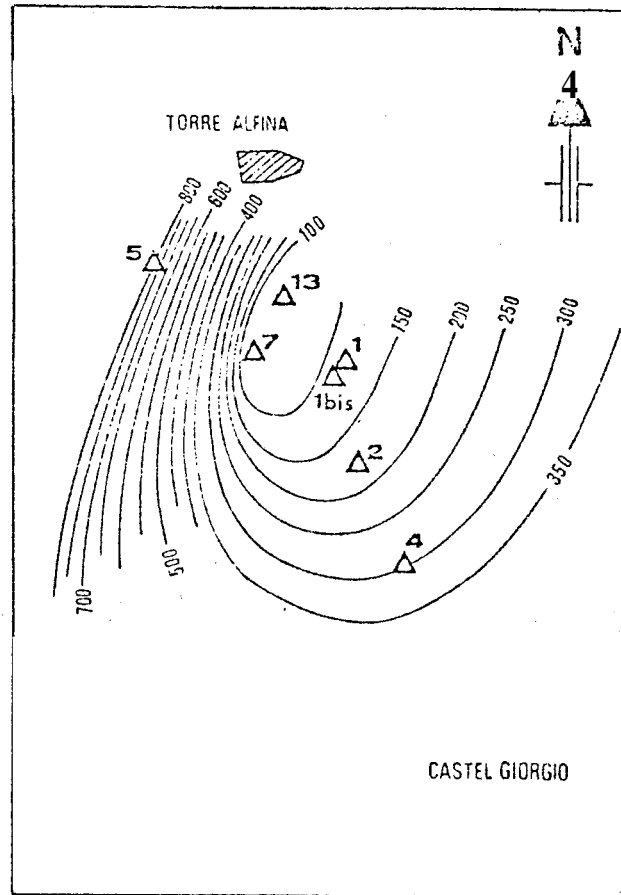


Fig 3 - CONTOUR LINES OF THE RESERVOIR TO?

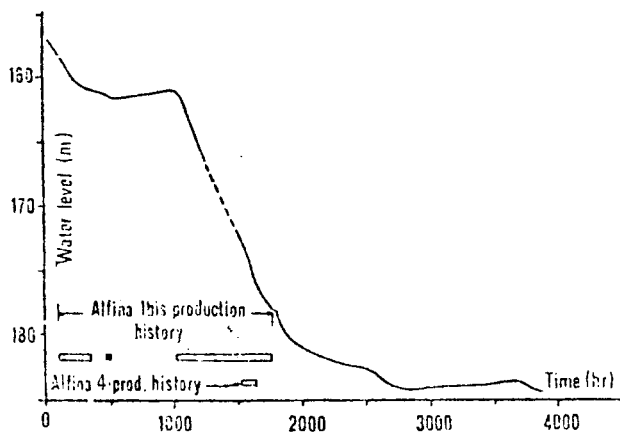


FIG.4-WATER LEVEL IN ALF2 WELL Vs TIME

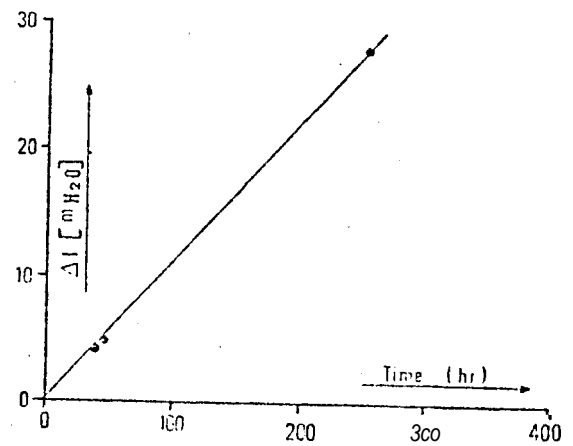


FIG. 5 -- DRAWDOWN IN ALF2 WELL Vs ALF1bis CUMULATIVE PRODUCTION

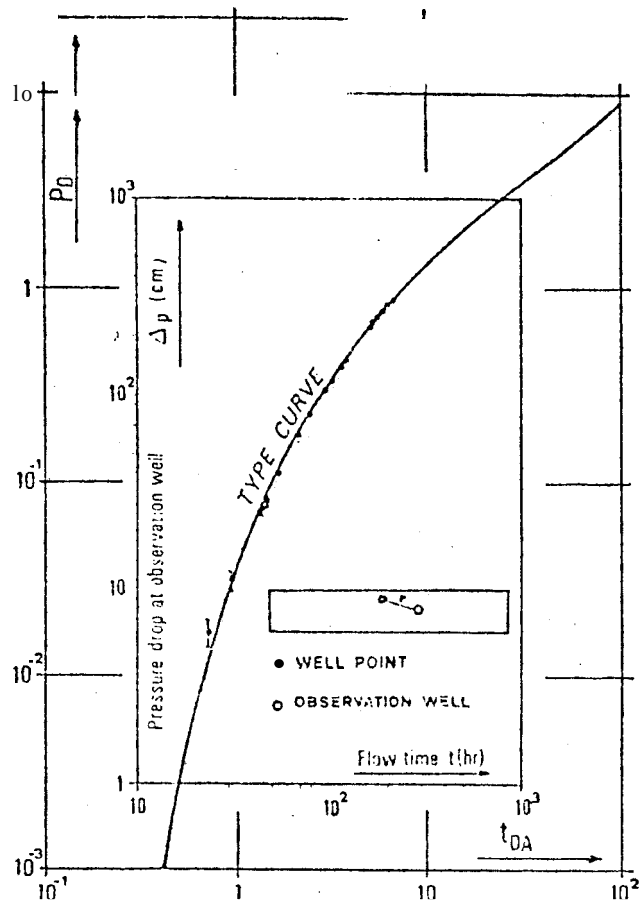


Fig.6 Type curve match for the closed rectangle considered

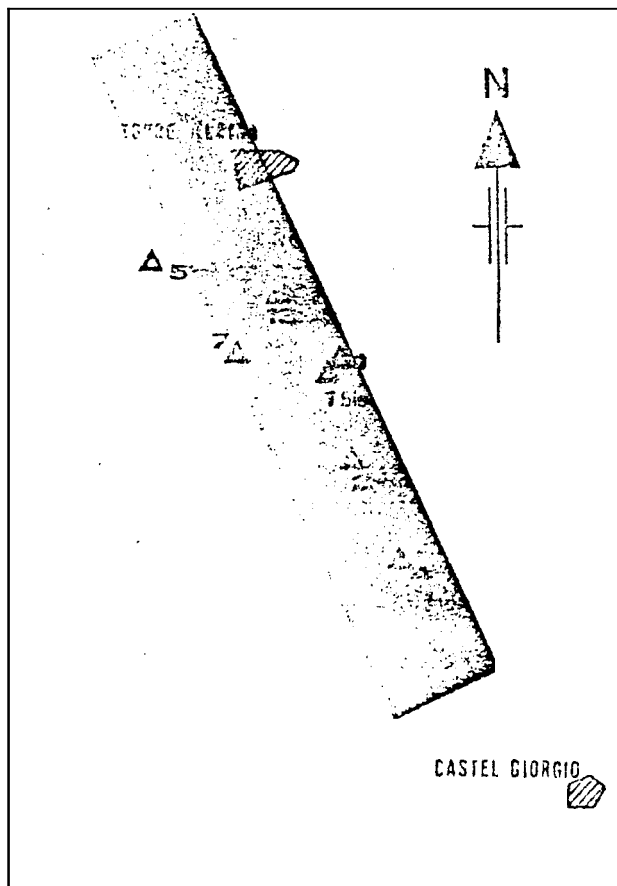


FIG.7- GEOMETRIC SHAPE CONSIDERED FOR THE RESERVOIR

HORNER METHOD APPLIED TO BUILDUP TESTS ON TRAVALE 22 WELL

A. Barelli, R. Celati, G. Manetti, and G. Neri*

Over a period of two years several Horner curves with different production times obtained from Travale 22 well were studied with a view to investigating the kind of boundary conditions existing in the reservoir.

Due to technical problems production history has often been very far from ideal, thus resulting in difficulties in analysis.

At fixed $1 + \frac{t}{\Delta t}$, P_D increases with an increase in t_{DA} , as expected for a well near impermeable boundaries, but all P_D approach zero when $\Delta t \rightarrow \infty$.

A contribution to pressure buildup from the boiling of a liquid phase cannot be excluded.

Travale 22 well was drilled in 1972 in Travale area, Tuscany, Italy, a few kilometers away from an area where some non-commercial wells had already been in existence for several years (Burgassi *et al.*, 1975).

This therefore was the first well to be drilled in the new area. During 1972 and 1973 there were several alternating periods of production and shut-in. Changes in production were often the result of technical problems and installation and maintenance operations so that the buildup data had to be gathered in non-ideal conditions.

Application of superposition principle

Several buildups are available from this period, with different production times, so that Horner plots

$$\frac{\pi h K M_w}{G \mu z R T} (p_i^2 - p_w^2) \quad \text{vs.} \quad \log \left(\frac{t + \Delta t}{\Delta t} \right)$$

with different "t" can be drawn.

A comparison between these curves and those taken from the available literature for many theoretical models (Figs. 1, 2, 3, 4, 5) can help towards an understanding of the nature, geometry and boundary conditions of the actual reservoir.

There is one difficulty when drawing these Horner plots for T22 well: p_i is not clearly determined in all the buildups, except for the first one. Every production period after this one began before shut-in pressure had stabilized so that the superposition principle must be applied.

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Let us assume the existence of a function $P_D(\tau)$ that remains unchanged throughout exploitation. So we can write (Fig. 8)

$$p_i - p(\tau) = \frac{\mu}{2\pi kh} \sum_{j=1}^n \Delta q_j P_D(\tau - \tau_j) \quad (1)$$

where $\Delta q_1 = q_1$, $\Delta q_2 = q_2 - q_1$, ..., $\Delta q_j = q_j - q_{j-1}$, and τ_j is the moment when the flow rate changes to q_j .

If a logarithmic approximation for P_D is adequate, (1) becomes

$$p_i - p(\tau) = \frac{q_1 \mu}{4\pi kh} \sum_{j=1}^n \frac{\Delta q_j}{q_1} \ln(\tau - \tau_j)$$

and a classical semilogarithmic graph is obtained by plotting

$$\frac{4\pi kh}{q_1 \mu} (p_i - p(\tau)) \quad \text{vs.} \quad \sum_{j=1}^n \frac{\Delta q_j}{q_1} \ln(\tau - \tau_j)$$

For our system the validity of the logarithmic approximation was doubtful for the whole shut-in period (Figs. 6 & 7).

As we wanted to compare our T.22 Horner graphs with those available for theoretical cases, we tried a different approach.

Let us consider, as in Fig. 8, two consecutive shut-ins and let $p_{\text{ext}}(\tau)$ be the value assumed by the pressure if the first shut-in were to continue to time τ .

In this case we have

$$p_i - p(\tau) = \frac{\mu}{2\pi kh} \sum_{j=1}^n \Delta q_j P_D(\tau - \tau_j) \quad (2)$$

and

$$p_i - p_{\text{ext}}(\tau) = \frac{\mu}{2\pi kh} \sum_{j=2}^{n-2} \Delta q_j P_D(\tau - \tau_j) \quad (3)$$

Combining these two equations we obtain

$$p_{\text{ext}}(\tau) - p(\tau) = \frac{\mu}{2\pi kh} \sum_{j=n-1}^n \Delta q_j P_D(\tau - \tau_j) \quad (4)$$

or, if q is the last flow rate

$$\frac{2\pi kh}{q\mu} (p_{\text{ext}}(\tau) - p(\tau)) = P_D(t + \Delta t) - P_D(\Delta t) \quad (5)$$

with t and Δt defined in Fig. 8. For gas wells, eq. 5 becomes

$$\frac{\pi kh M_w}{G\mu zRT} (p_{\text{ext}}^2(\tau) - p_{ws}^2(\tau)) = P_D(t + \Delta t) - P_D(\Delta t) \quad (6)$$

The theoretical Horner plot gives $P_D(t + \Delta t) - P_D(\Delta t)$ vs $\log\left(\frac{t + \Delta t}{\Delta t}\right)$

If we are able to extrapolate the previous buildup curve so that a sufficiently approximate value is obtained for $p_{\text{ext}}(\tau)$, we can use the left hand side of eq. (6) to construct Horner plots from field data. These can then be compared with the available Horner plots of theoretical cases to obtain information on the most suitable model for the real situation.

Horner Plots for Travale 22 Well

The curves shown in Fig. 9 were plotted according to the above procedure. Some buildup curves were excluded there being no possibility of obtaining reliable values for $p_{\text{ext}}(\tau)$; for this same reason some other curves were shortened in their final part although further shut-in pressure data were available.

Production time t is reported as a parameter instead of t_{DA} as the hydraulic diffusivity and reservoir area are not known.

The kh value used to calculate $\frac{\pi h K M_w}{G \mu z R T} (p_{ext}^2 - p_{ws}^2)$

was obtained by conventional Horner plots and type-curve matching (Barelli et al., 1975).

Some very short delivery during long shut-ins and very short shut-ins during long production periods have been ignored.

From Fig. 9 we can observe that:

- there is a regular displacement of the curves changing t ;
this displacement is such that the dimensionless Δp^2 is an increasing function of t for any given $\frac{t + \Delta t}{\Delta t}$
- $(p_{ext} - p_{ws}) \rightarrow 0$ when $t \rightarrow \infty$.

This is not so clear in Fig. 9 as some curves are not complete, due to the difficulty in extrapolating the previous curve.

The trend to recovery of initial pressure is evident in Fig. 7 which represents a very long buildup occurring about nine months after well blow-out.

Similar results were found by Celati and Galardi (1975) with a simplified analysis, assuming for p_i a constant value or the maximum value reached in the last long buildup.

From a comparison of T 22 curves with the theoretical cases given in Figs. 1 to 5, we see that downward displacement is generally obtained as the effect of impermeable boundaries as in Fig. 1 and, for a limited range of t_{DA} in Fig. 3. The same kind of t -dependence of the curve position is obtained for an infinite reservoir with linear or radial discontinuity when the well is placed in the higher mobility zone. The limiting hypothesis of constant diffusivity throughout the reservoir was formed for these cases. The curves in Figs. 4 and 5 are the most similar to those of T 22, as they also have similar trends for $\Delta t \rightarrow \infty$. In the case of a closed reservoir the asymptotic values for $\Delta t \rightarrow \infty$ are positive, increasing with an increase in t and, in the case of recharge through a limited section in the boundary, the curves intersect one another in the final part of the buildup.

However, the latter effect is much less evident for smaller values of t , and in our case it could be masked by experimental errors and the fact that the curves are not generally extended to very long Δt values.

Discussion and Conclusion

Some hypotheses can be drawn from these observations, although the results are insufficient to draw definite conclusions.

From the geological point of view, Travale 22 is located in a structural high of the reservoir formation connected with the recharge area to the west and bounded on its N, E, S sides by faults; the latter lower than the reservoir formation and putting the upper part of the structure in lateral contact with impermeable formations.

Geological hydrological and chemical data, obtained from other wells in the zone, have shown:

- an interference between the vapor-dominated system feeding T 22 and the water-dominated system in the old wells area,
- sudden decreases in permeability outside T 22 area,
- a limited connection between the structural high and the deeper surrounding reservoir (Burgassi ~~et al.~~, 1975).

The hypothesis of a high permeability zone surrounded by lower permeability zones agrees both with the geological information available and the similarity between the curves of T 22 well and those of Figs. 4 and 5. The theoretical case considers a linear or radial discontinuity, in mobility and a uniform diffusivity, whereas the actual situation, although not completely known, may certainly be considered rather more complex. The complex geometry may be responsible for the shape of the buildup curves. However, we consider it very likely that a contribution to the pressure buildup comes from the boiling of liquid water both on the boundary of, and inside, the vapor dominated zone.

The reduction in pressure can favor the infiltration of liquid water from the relatively cold boundaries toward the warmer parts of the reservoir.

These observations are based on two-dimensional models. As there are doubts as to the validity of purely radial flow models, a three-dimensional model is now being constructed.

For a quantitative comparison of the various models with the field data we are going to use log-log instead of conventional semi log Horner graphs. A match obtained with vertical displacement only will let us choose the most suitable family of curves and determine kh and t_{DA} .

Nomenclature

- a = distance from well 1 to the linear discontinuity
- A = reservoir area
- c = compressibility
- Fs = storage capacity ratio
- G = mass production rate
- h = reservoir thickness
- k** = permeability
- M = mobility ratio
- Mw = molecular weight
- p = pressure
- P_D = dimensionless pressure
- p_{ext} = extrapolated shut-in pressure
- p_i = initial pressure
- p_{ws} = shut-in pressure
- q = volume production rate (reservoir condition)
- R = gas law constant
- t = production time
- t_D, t_{DA} = dimensionless time
- T = absolute temperature
- z = compressibility factor
- $\Delta p = p_i - p_{ws}$
- At = shut-in time
- Φ = porosity
- μ = viscosity
- τ = time

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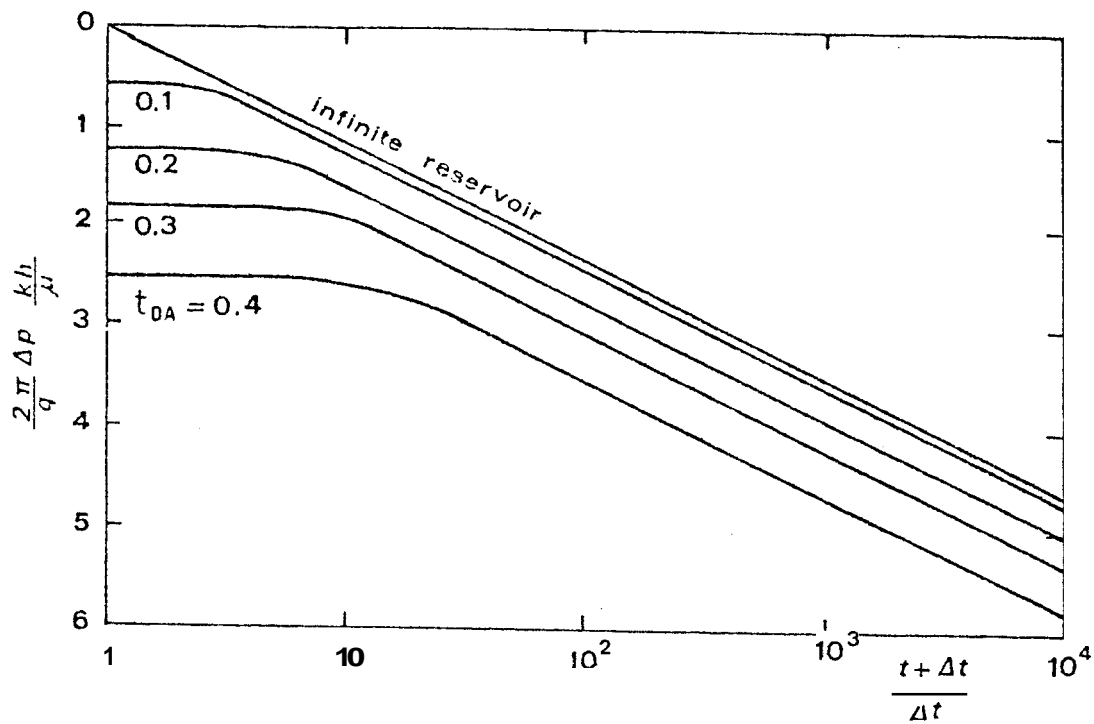


Fig. 1 - Horner plot for a well in the centre of a closed square.

$$t_{DA} = \frac{kt}{\phi\mu cA} \quad \text{(Ramey et al., 1971).}$$

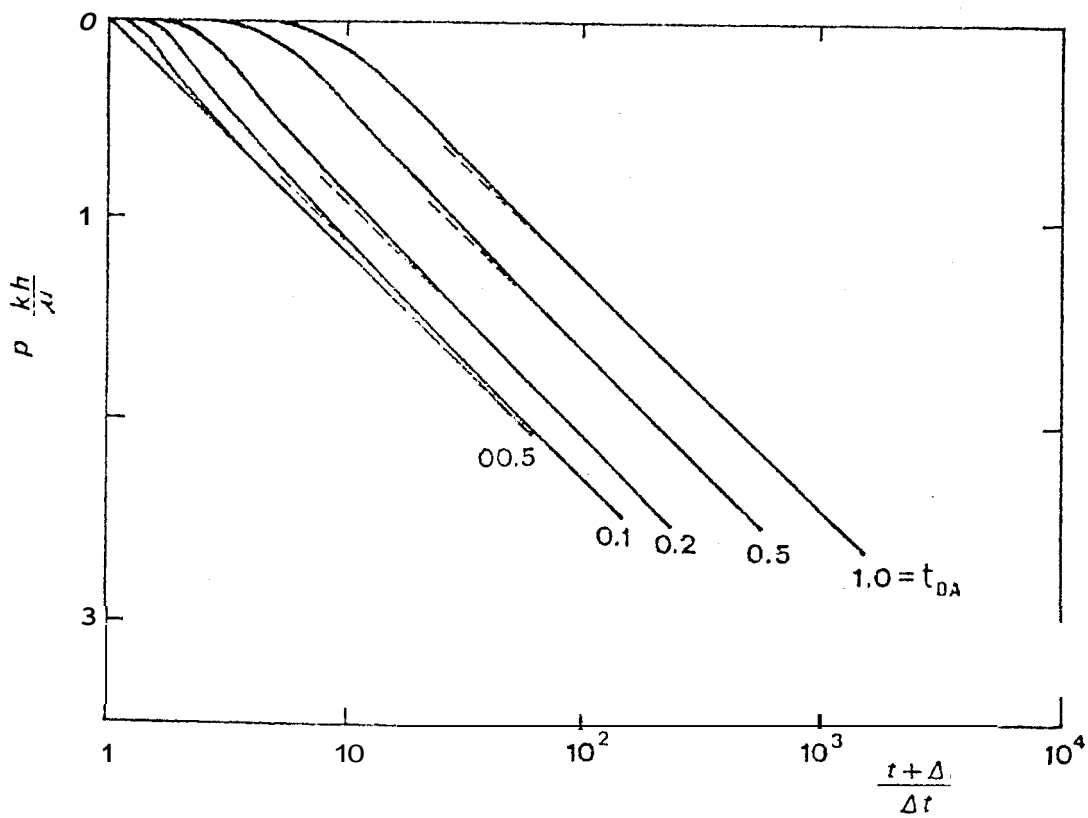


Fig. 2 - Horner plot for a well in the centre of a constant pressure square

$$t_{DA} = \frac{kt}{\phi\mu cA} \quad \text{(Ramey et al., 1973).}$$

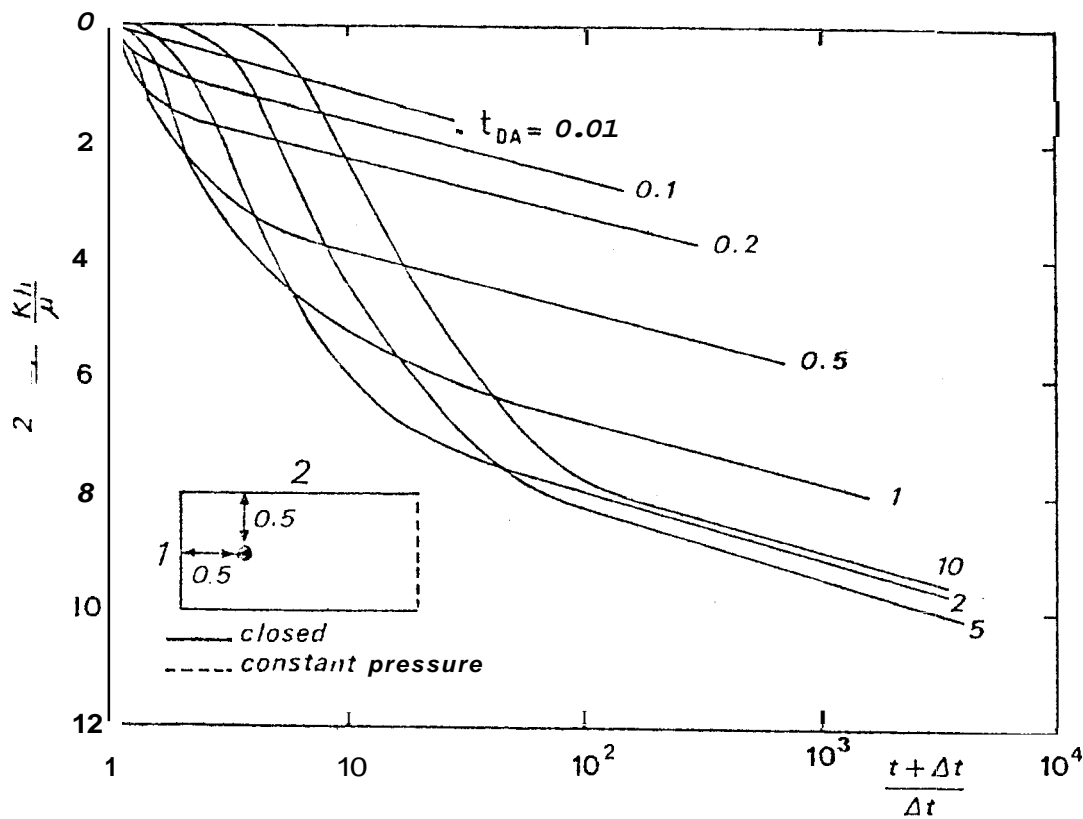


Fig. 3 - Horner plot for a well in a 2 : 1 rectangle with one short side at constant pressure (well position: see fig., $t_{DA} = \frac{Kt}{\phi \mu c A}$) (Ramey *et al.*, 1973).

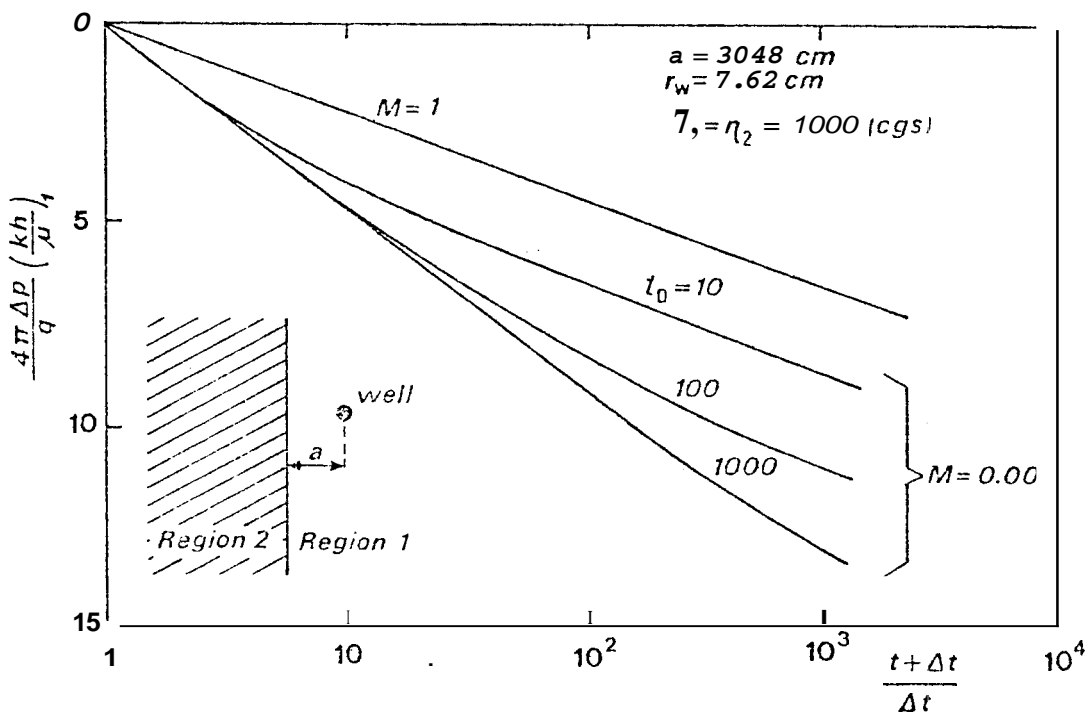


Fig. 4 - Horner plot for linear discontinuity case (Bixel *et al.*, 1963)

$$t_D = \frac{k_1 t}{\phi_1 \mu c_1 \Omega^2} ; M = \frac{(k/\mu)_2}{(k/\mu)_1}$$

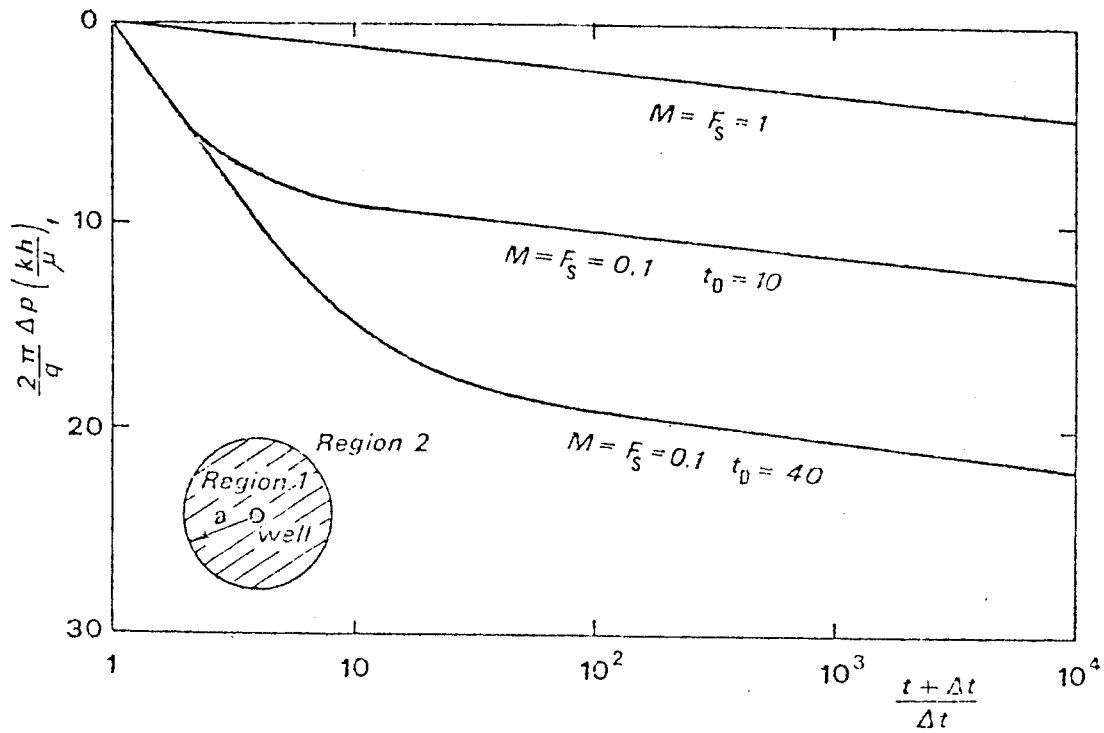


Fig. 5 - Horner plot for radial discontinuity case (Bixel et al., 1966)

$$t_{D2} = \frac{K_1 t}{\phi_2 \mu c_1 \Delta z^2} ; M = \frac{(k/\mu)_2}{(k/\mu)_1} ; F_s = \frac{(\phi c)_2}{(\phi c)_1}$$

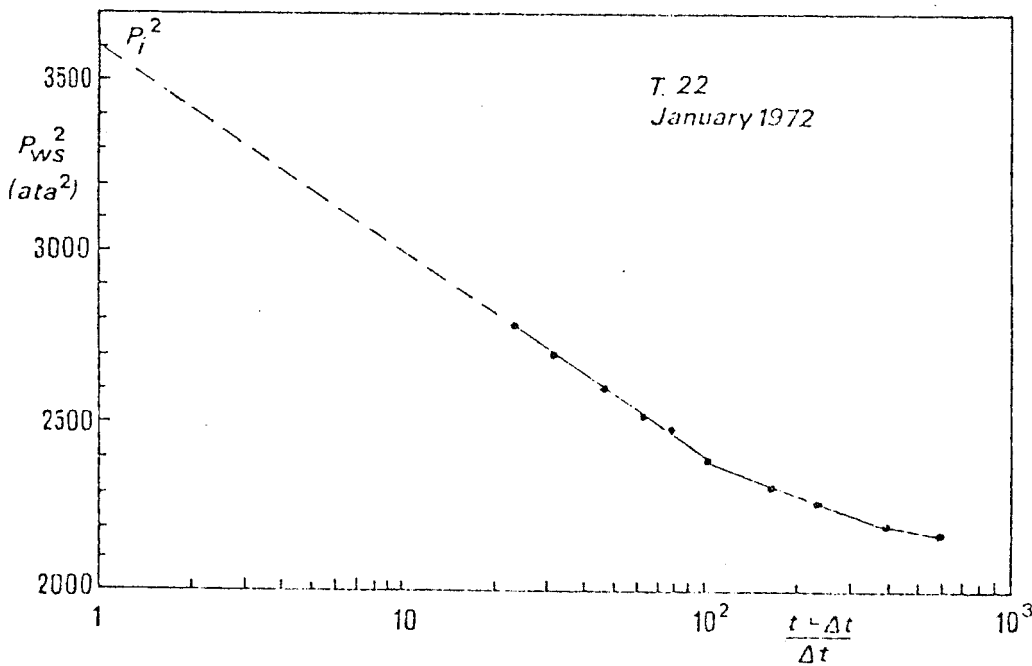


Fig. 6 - First shut-in curve for T 22 well.

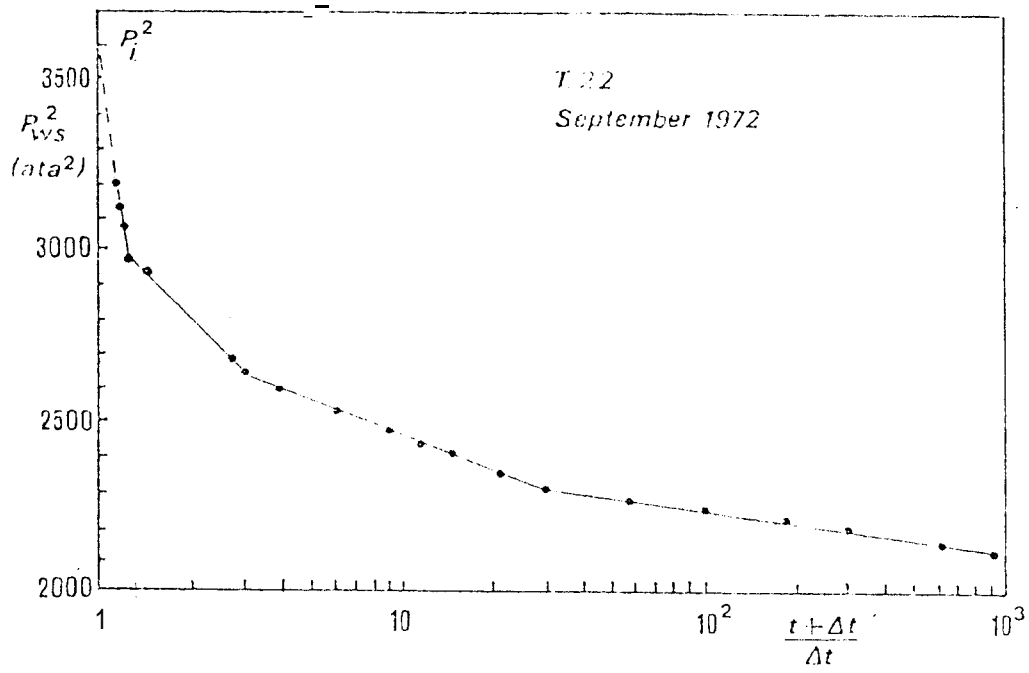


Fig. 7 - Shut-in curve for T 22 well.

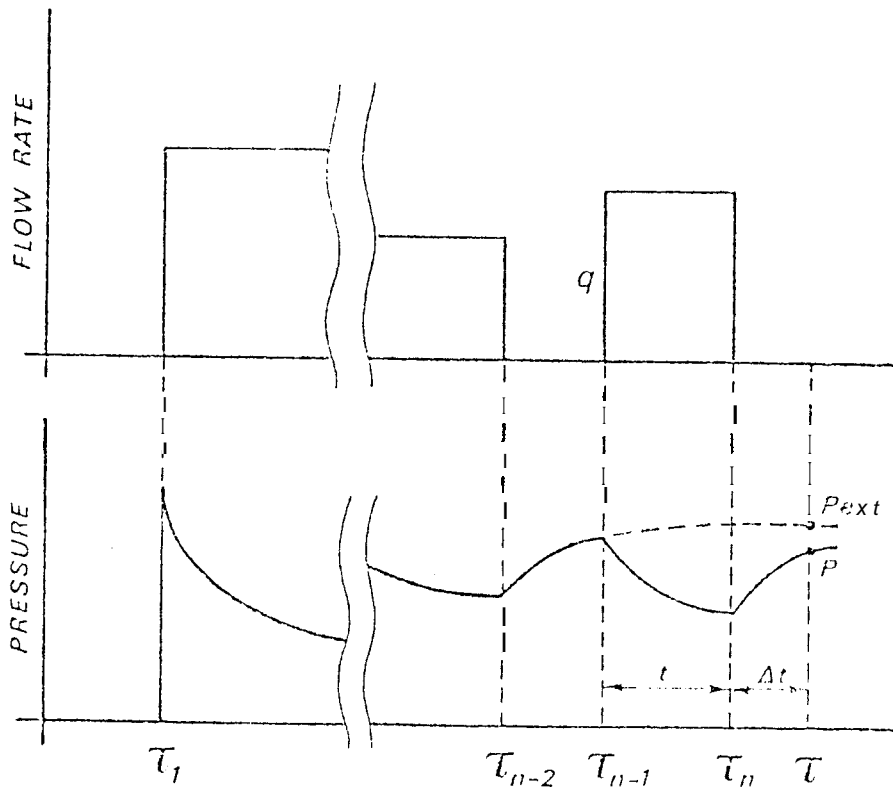


Fig. 8 - Design showing application of superposition principle.

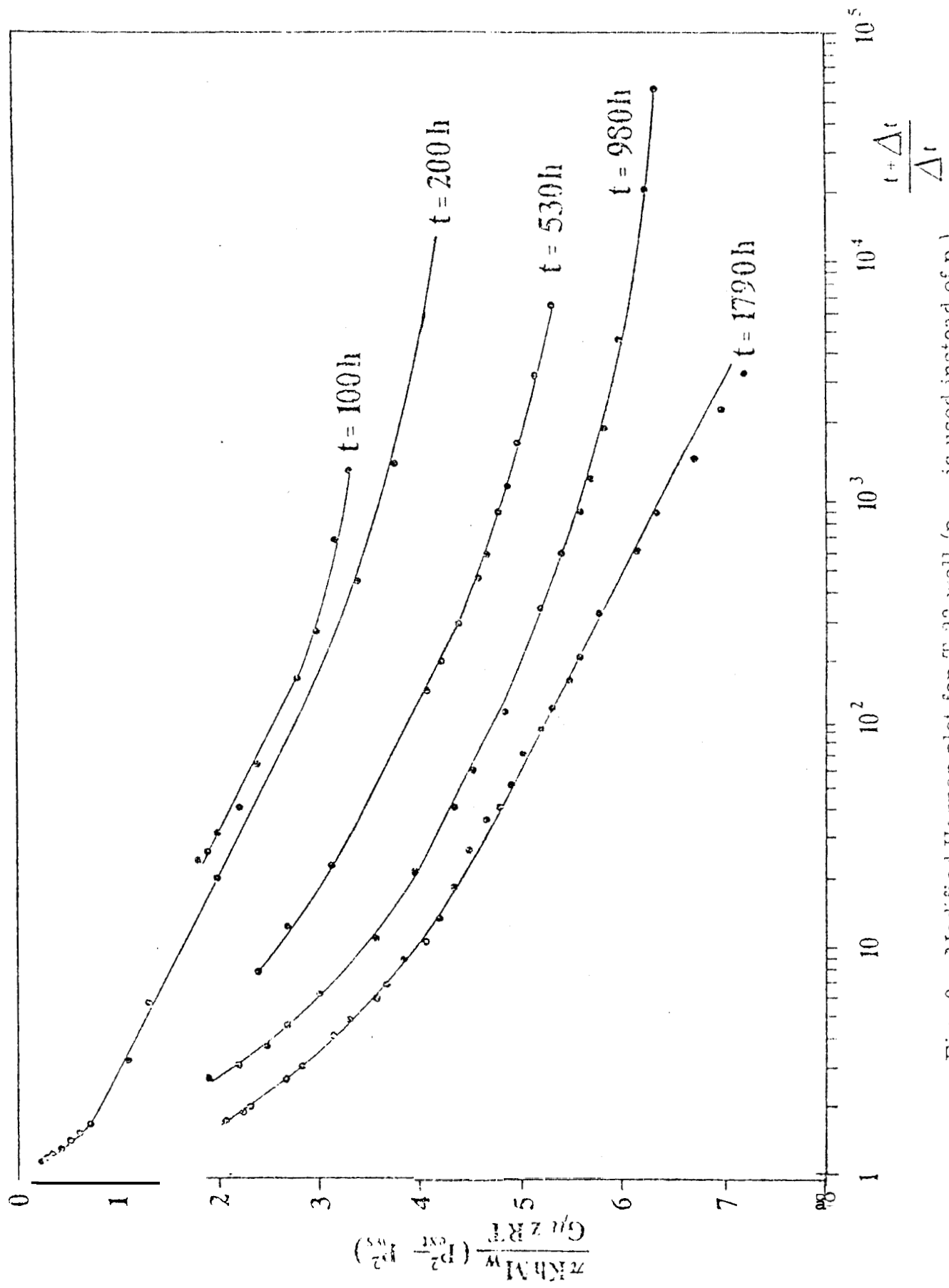


Fig. 9 - Modified Horner plot for T 22 well (p_{ext} is used instead of p_i).

STUDY OF A GEOTHERMAL FIELD IN THE ASAL ACTIVE VOLCANIC RIFT ZONE
(FRENCH TERRITORY OF AFARS AND ISSAS, EAST AFRICA)

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The Asal rift, located 80 km west of Djibouti, is one of the active "rifts-in-rift" structures of the Afar depression, a transition between the Gulf of Aden and the Red Sea ridges (Fig. 1).

Attention was drawn to this zone because of the presence of a graben structure, and of geochemical particularities of various hot springs. Two wells were drilled on the S-W margin of the rift, at locations chosen mainly from geological considerations. The first hole reached a hot water geothermal reservoir, the second, one kilometer away, was dry.

Both wells found, from top to bottom, a recent basaltic series, then a thick rhyolitic volcanic series, and finally an old tectonic, tilted, basaltic series, where the reservoir is located. The first well was drilled to a depth of 1130 m, where heavy mud losses occurred, while the second well reached 1550 m. An important normal fault appears to separate the two wells.

The first well, which had to be induced into production by air-lift, was used for extensive well testing.

Permeability information was obtained prior to production by injection of cold water. Although the bottom hole pressure was perturbed by thermal effects from mixing within the tubing of injection and reservoir water, analysis could be performed with the semi-log straight line method, and yield a kh value of 2 darcymeters. Buildup and drawdown tests were also performed, but provided unusual pressure responses (Fig. 2). Although the reservoir was expected to be fractured, no fracture effect was apparent on a log-log plot. Pressure at the bottom of the well stabilized rather abruptly within 10 minutes after the beginning of either a buildup or drawdown test, which might indicate the existence of a recharge boundary nearby.

Numerous temperature and pressure logs were run in the well, before and during production (Fig. 3). These indicated initial conditions of 253°C and 77kg/cm² at 1050 m, which was the maximum depth reached with the Kuster recorder. Pressure and temperature logs during production clearly showed the existence of a flashing front within the wellbore.

The well production rate was varied by means of pipes of different diameters at the wellhead. Sampling of the geothermal fluid at the wellhead failed to provide reasonable values of flow rate and enthalpy. These were obtained by comparison with theoretical results from a numerical model provided by M. Nathenson (Fig. 4). Although the flow system at the Asal field seemed to be different from that considered in the model, agreement between measured and computed values was very good. It was concluded that the maximum

production of the well was of the order of 135 t/hr, with 20% steam at the wellhead. This, with a wellhead temperature of 170°C could provide 1 or 2 MW of electric power.

Chemical analyses of the geothermal fluid indicated very high salt content, of the order of 190 g/l, which was also found to increase with production time. This, and other evidences, might indicate the existence of an active convection cell.

interpretation of the various data collected on the field is continuing, and results will be made available in the near future.

Reference

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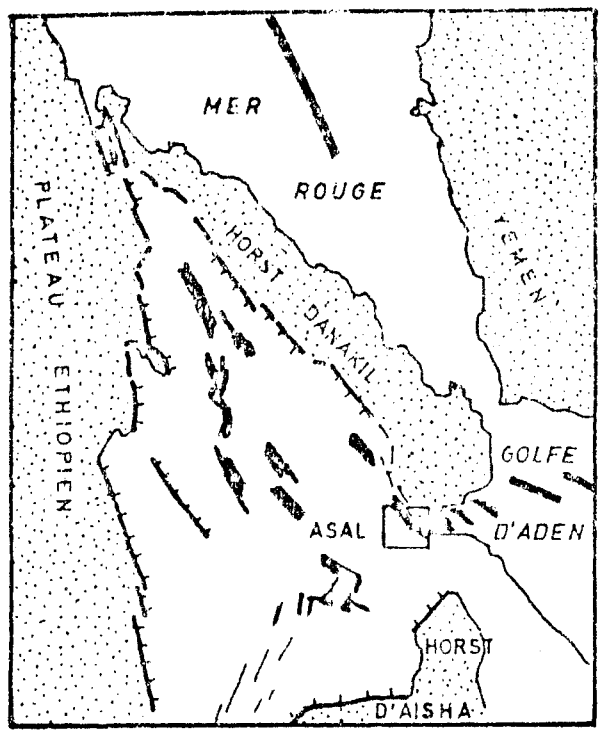


Figure 1

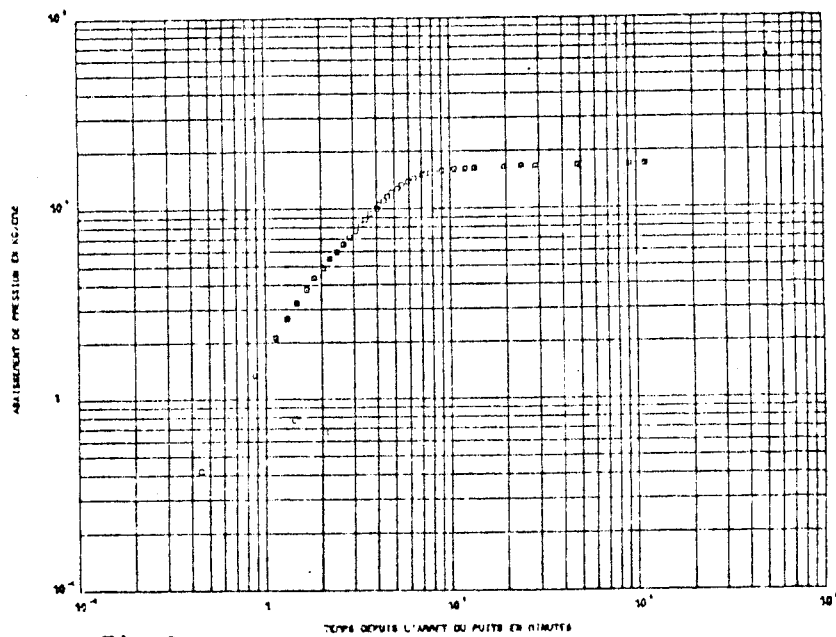


Fig 2: ESSAI DE REPONTEE EN PRESSION SUR ASAL (SCATIE 4° LE 1-11-75)

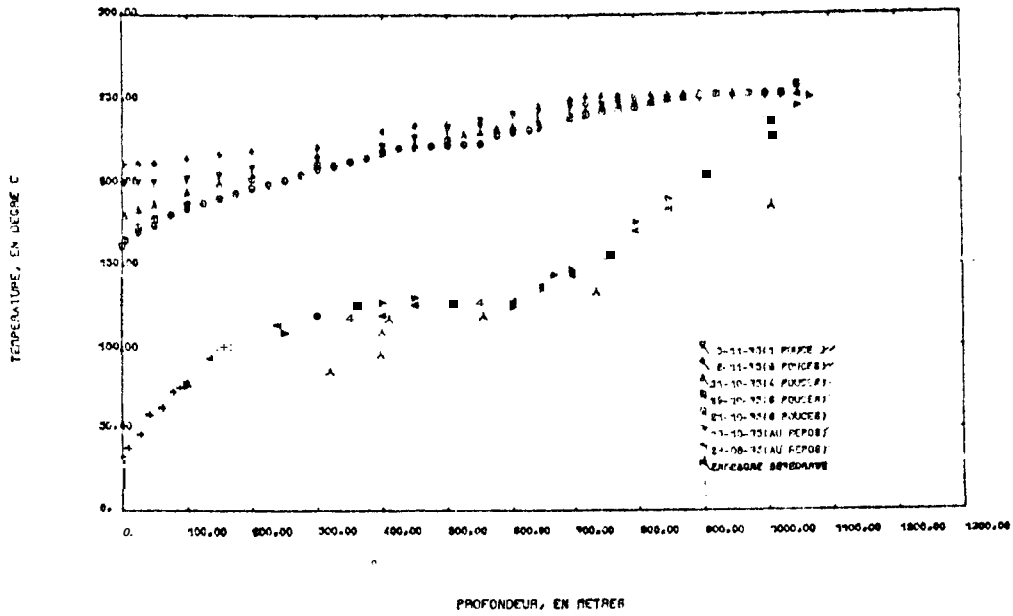


FIGURE 3 : MESURES DE TEMPERATURE DANS ASAL 1

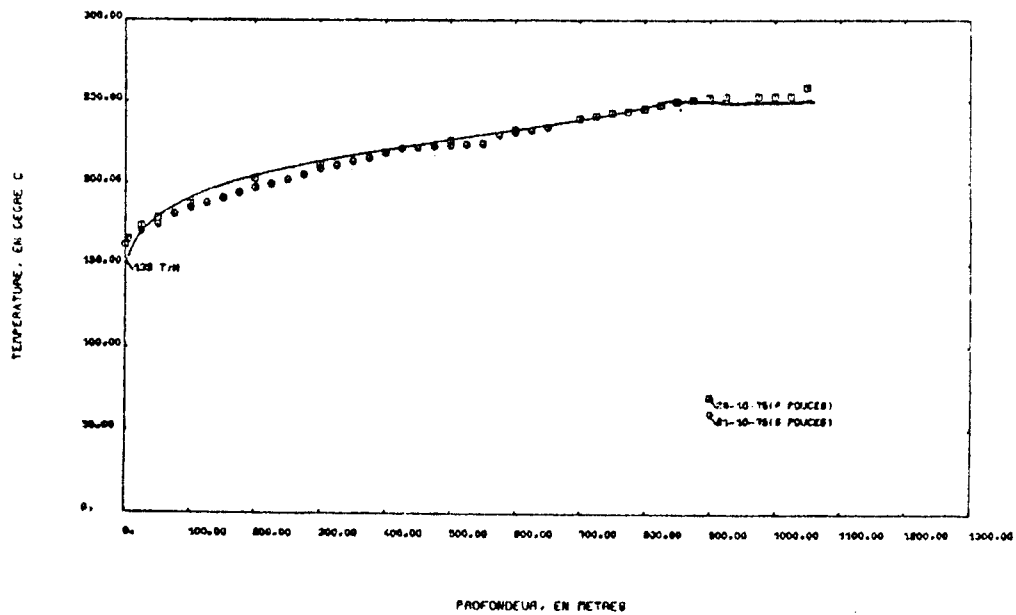


FIGURE 4 : ASAL 1-COMPARAISON ENTRE LES MESURES DANS LE PUIT ET LES PREVISIONS DU PROGRAMME WELL (KH=2 DARCYMETRES, CONDITIONS DE FOND: 250 DEG C ET 86 BARS)

RAFT RIVER GEOTHERMAL RESERVOIR ENGINEERING AND WELL STIMULATION

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In 1973 the Idaho National Engineering Laboratory (INEL) was funded by the Energy Research and Development Administration (ERDA) to pursue a program of research and development into the geothermal potential of the Raft River Valley, Cassia County, Idaho. A cooperative effort was then undertaken involving Aerojet Nuclear Company, U.S. Geological Survey, State of Idaho, and the Raft River Rural Electric Cooperative.

The basic geological investigations (principally the USGS) were completed in late 1974. A meeting was then held to present all available data and select a drilling site for RRGE-1. The site was finally located in the middle of Section 23, R26E, T15S. The second site, RRGE-2, was located in the extreme northeast corner of Section 23.

Geologic Structure

The Raft River Valley is a typical downfaulted north-trending basin lying in the northern portion of the Basin and Range province. The basin is terminated on the north by the Snake River Plain of the Columbia River Plateau province. The major local structural control consists of the Narrows structure (NE-SW) and the Bridge Fault (N-S) as depicted in Fig. 1.

RRGE-1 and RRGE-2 Wells

The Raft River Valley is composed of young alluvium derived from the surrounding mountain ranges, tuffaceous silt and clay of the Raft Formation; tuffaceous silt and sandstone of the Salt Lake Formation and quartzite and quartz monzonite of the Pre-Cambrian basement complex. Cross-sectional views of RRGE-1 and RRGE-2 are shown in Figs. 2 and 3.

The essential information pertaining to both wells is listed below

	<u>RRGE-1</u>	<u>RRGE-2</u>
1. Drill start date	1-4-75	4-27-75
2. Drill completion date	3-31-75	6-27-75*
3. Average flow	650 gpm	800 gpm
4. Maximum bottom temperature	294°F (146°C)	297°F (147°C)
5. Total depth	4989 ft.	5988 ft*
6. Main production	4350-4900 ft	4300-5000 ft
7. "Hot" shut-in pressure	~11 atm	~10 atm

*RRGE-2 may be deepened by 500 feet in an attempt to further enhance natural artesian production.

Reservoir Engineering

1. Downhole Logging

Several standard and special well logs were run in both wells and include the following:

temperature, caliper, natural gamma, compensated neutron-formation density, dual induction-laterolog, spontaneous-potential, dipmeter, compensated gamma density, sonic, televiewer, and flowmeter.

2. Coring-Sample Testing

Several cores were taken at different depths in both wells. Permeability varies from 0.002 millidarcies for tight caprock to 5-10 millidarcies for some producing tuffaceous sediments as measured under "in situ" condition. Further pressure testing of the aquifer have included fracture permeability and indicate much higher aquifer permeability.

3. Flow Testing

Both RRGE-1 and RRGE-2 have undergone extensive flow testing over extended periods of time (5 weeks at 200-400 gpm). RRGE-2 discharges approximately 800 gpm just prior to reaching the flash point at the surface, starting from a subcooled condition. Once flashing begins, the back pressure generated is a result of the discharge nozzle configuration and determines the total mass flow. For instance: with 275°F outlet temperature at the wellhead, the maximum natural flow is only about 400 gpm with the present piping and flasher-separator equipment.

The water quality remained very constant during the extended flow testing averaging 2,000 ppm solid content.

A downhole temperature recorder was run in RRGE-2 several times under flow and static shutin conditions. Under static conditions, the temperature was 290°F at the bottom of the casing (4230 ft) and 297°F at the bottom of the well (5988 ft). Prior information had indicated very little production from below 4800 ft. Such a temperature gradient represents an unusual situation for a non-producing zone. The gradient of 7°F/1758 ft is much less than even a normal gradient of 2°F/100 ft that one would expect. This anomaly may be the result of a "hot plate" effect near the bottom of the well, with circulation above that is apparently not entering the well to any great extent below 4800 ft.

4. USGS Data Correlation

The coring, logging, and drilling information provided the data necessary to make a correlation between the well lithology and the USGS geophysical data acquired in the area. The well information agreed totally with the interpreted geophysical data except for the basement rock type. It was logically inferred, from geophysical data, that the basement rock would be Paleozoic sediments. However, the Paleozoic rock sequence, as well as Mesozoic, are apparently missing within the basin.

5. Well-Killing Technique

RRGE-1 was drilled into the production zone before the production casing (13-3/8 in.) was emplaced. This necessitated "killing" the artesian flow from the well in order to install the casing. Cold water injection into the well proved unsuccessful in stemming the flow. The well was filled with 881 ft of sand and a cement plug (120 ft) installed which allowed casing to be set.

Reservoir Modeling

From the limited data, it would appear that the majority of geothermal water originates in the Almo Basin (next valley west of Raft River) and feeds a large reservoir in the Raft River Valley. Only about 22% of the annual precipitation in the Almo Basin can be accounted for by surface runoff. Further investigation is continuing to affirm this model.

Power Plant Development

Geothermal power plants operating from medium temperature (about 150°C) water can be expected to generate 1 MW (net electric) for every 250,000 lb/hr of geothermal water (the best of wells can be expected to produce 1 million lb/hr. or 2000 gal/min. or 120 liters/sec). Normal well spacing will dictate that a power plant feeding from a 4 to 10 square mile area of reservoir might generate typically 50 MW(e). A larger plant module will pull from a still larger area, needing longer pipelines, and offsetting any cost advantage of lower unit cost of the power plant equipment. Thus, it appears that 50 MW is the nominal optimum size. Such a plant will be rejecting 300 to 400 MW of waste condenser heat; and the question is how to best accomplish this rejection of heat. Once-through condenser cooling from the near surface cold water aquifer seems a likely method. The net effect would then be transfer of heat from the geothermal aquifer to the near surface aquifer, except for 10 to 15% converted to electricity. The efficiency of the power plant would be significantly improved as the condenser operated at 20°C instead of 35 to 45°C as with cooling towers.

Reservoir engineering of the withdrawal and reinjection from the cold water aquifer has received as much attention in the Raft River Program as the reservoir engineering from the geothermal aquifer. Fortunately, nature usually provides more and larger cold water aquifers than geothermal aquifers, so solving the condenser cooling requirements should not be as difficult as supplying the heat input to the plant. It should be noted that such once-through condenser cooling is only pertinent for small power plant modules (approximately 50 MW). For instance, a 2000 MW(th) heat rejection requirement such as that of a large nuclear plant would need to draw and reinject from too large an area to make piping the water an economic practicality in most situations.

Well pumping tests have been conducted over the last year, from which transmissivity and storage coefficient have been determined. Application of these to a digital computer reservoir model show that the cooling requirements for a 50 MW power plant can be supplied with a well pattern that has drawdowns and "drawups" (from reinjection) of less than an atmospheric equivalent pressure head over many years of operation.

Well Stimulation

1. Water Drilling - drilling with water through the production zone in both wells has proven highly successful. This method has eliminated the possible sealing of the production zone by mudcake.

2. Hydrofracturing - RRGE-1 was subjected to limited hydrofracturing employing the drilling rig mud pumps at 550 gpm and 1400 spi for short periods (up to 3 hours). No noticeable effect was observed in increased production.
3. Drill Stem Testing - a drill stem test was conducted on RRGE-2 at the bottom of the hole (4247 ft) before production casing was installed. The test showed no flow from the bottom 90 ft of the hole. Drilling was conducted using mud to this depth. Immediately upon drilling deeper with water, flow was encountered.
4. Side-Track Drilling - investigation is being conducted at present to evaluate the potential production benefits to be derived from drilling two and three holes off the main hole.

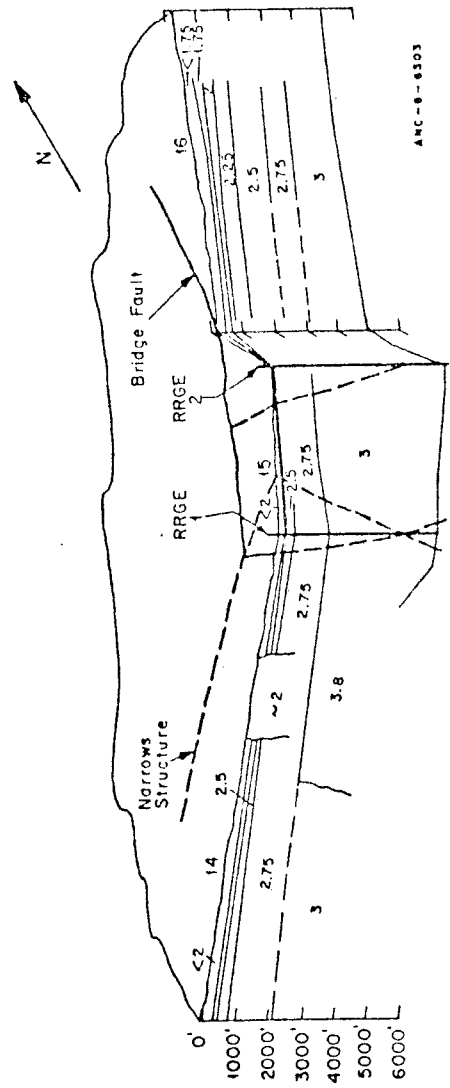


Fig. 1 Geologic Structure, RRGE-1 and RRGE-2, Raft River Valley, Idaho

RRGE NO. 1

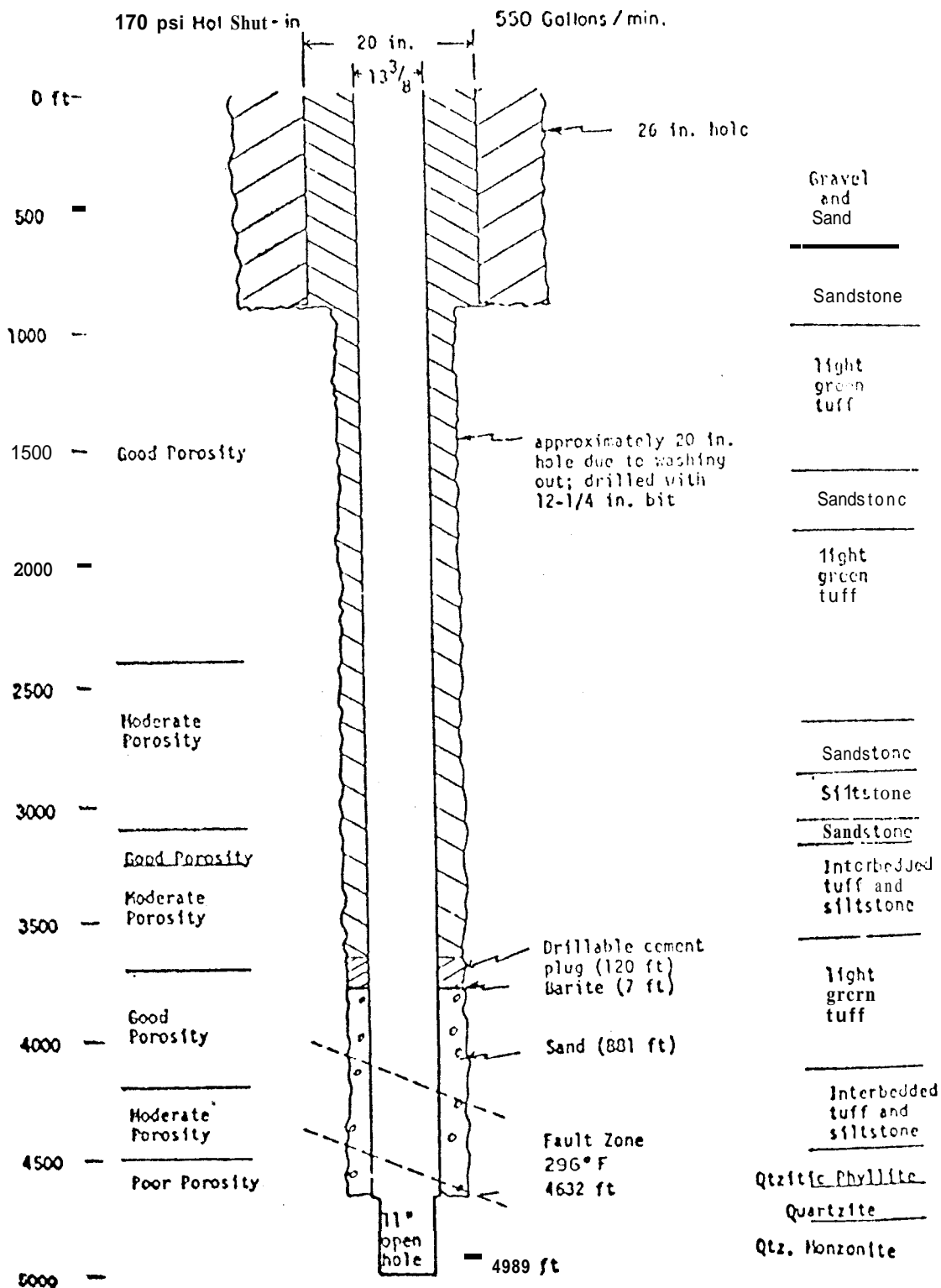


FIGURE 2.

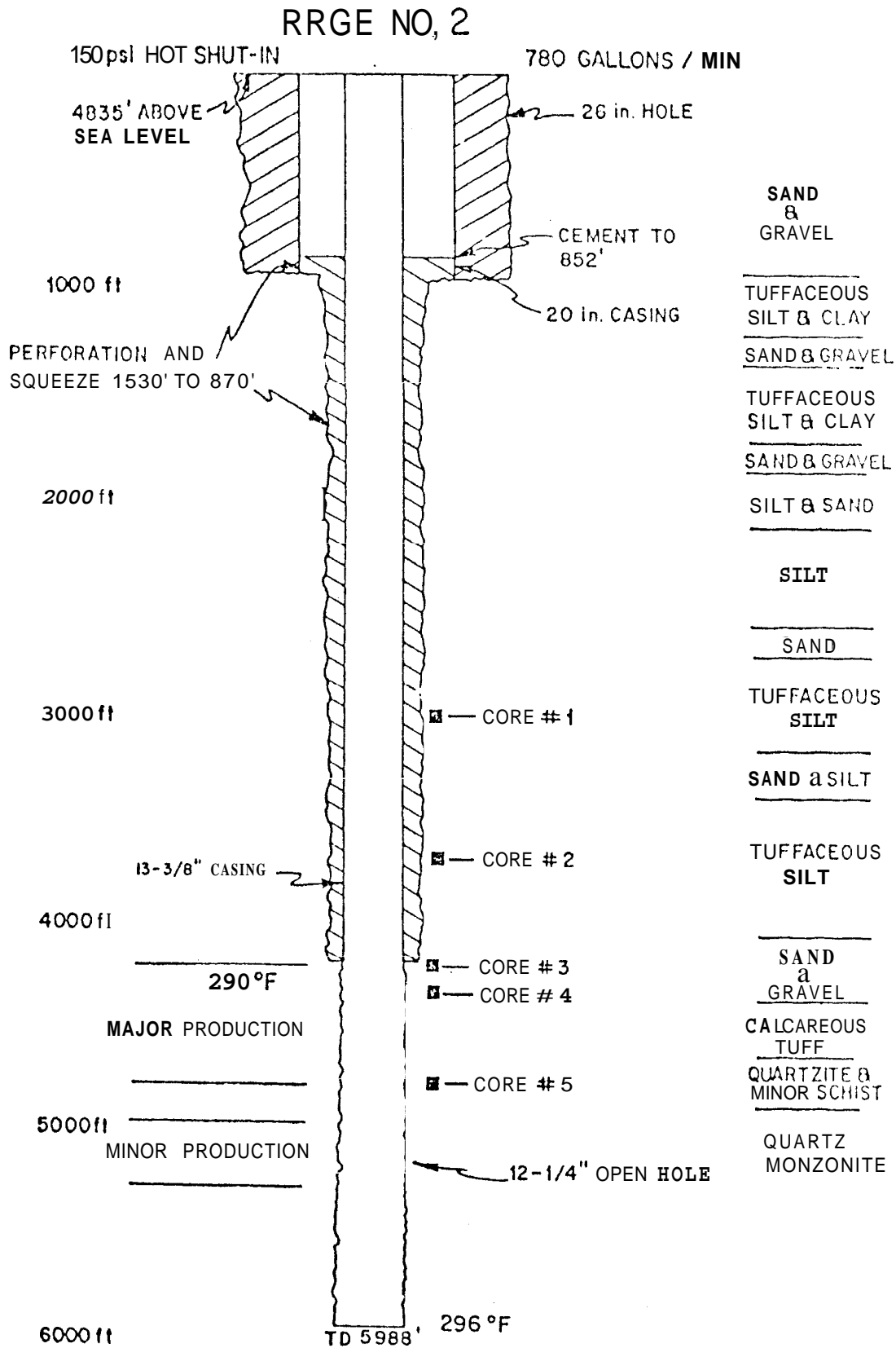


FIGURE 3.

INITIAL RESULTS OF RESERVOIR PRODUCTION TESTS,
RAFT RIVER GEOTHERMAL PROJECT, IDAHO

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Two geothermal test wells were drilled and completed in Raft River Valley, Southern Idaho by the Idaho National Engineering Laboratory between January and August, 1975. Subsequently, hydraulic tests were conducted on these wells to make preliminary estimates of the geothermal reservoir parameters and reservoir geometry. The purpose of this presentation is to discuss the data obtained from these tests.

Geological Setting

The Raft River geothermal area lies in a north-trending, warped and down faulted basin, filled with tufaceous sandstone, siltstone, coarse-grained sandstone and shale (the Salt Lake formation of Mio-Pliocene age). In the vicinity of the test wells, the Salt Lake formation overlies a quartz-monzonite bed rock of Precambrian age. In both test wells [RRGE #1, 4989 feet deep and RRGE #2, 5988 feet deep] hot water at approximately 294°F (146°C) was tapped at the base of the Salt Lake formation. Both are artesian wells with shut-in well-head pressures of about 150 psi. The bottom hole pressures at a depth of 5000' were about 2200 psi. If opened to the atmosphere, each well can flow freely up to 800 gpm. The distance between the two wells is approximately 4000 feet.

The Hydraulic Tests

The hydraulic tests conducted on these wells extended between mid-September and early November. The tests principally consisted of flowing either of the wells at controlled rates and observing pressure changes either in the flowing well itself or in the non-flowing well. A key piece of equipment in these tests was a sensitive quartz pressure gauge capable of an accuracy of .001 psi. A summary of the tests conducted is contained in Table 1.

An important feature of the pressure transient data collected, especially during tests 2 and 3, was the remarkable response of the reservoir pressure to the gravitational changes induced by the passage of the moon. Comparison of the observed pressure changes with the earth tide computations made by Dr. Howard Oliver of the U.S.G.S. at Menlo Park for the period of observation indicated a maximum earth tide-induced perturbation of about 0.2 psi in reservoir pressure while the maximum change in gravity over the same period was about 0.25 m gal. In order to use the data for reservoir interpretation appropriate corrections had to be made for the earth tide-induced perturbations. A quick way to eliminate such perturbations was to consider only those pressure measurements corresponding to the times at which the earth-tides had zero magnitude.

The long duration interference test (test 2) indicated that between the two test wells the reservoir has an overall $kH = 2.28 \times 10^5$ md feet and an overall ϕCH of 1.2×10^{-3} ft/psi. Careful study of the early pressure buildup data failed to indicate the presence of unit slope or half-slope line segments on the log-log paper, suggesting the absence of either well-bore storage effects or the effects due to prominent fractures. The system appears to behave, in a bulk sense, as a homogeneous reservoir.

Test 1 indicated that there possibly exist one or two barrier boundaries close to well No. RRGE #2. Test 2 indicated the possible presence of one barrier boundary. With only two test wells it has not been possible to locate these barrier boundaries.

The results of the hydraulic tests conducted so far suggest that the geothermal reservoir in Raft River Valley is fairly large and permeable and is of considerable practical interest.

TABLE 1

TEST DATA FOR RRGE WELLS

Test No.	Description	Duration (hours)	RRGE Well No.	Flow Rate (gpm)	Max. Pressure Drop (Δp , psi)	Depth, (feet)
1	Short Term Test	17	2	210	39	5200
2	Long Term Test	615.5	2	400	3.6	1000
3	Short Term Test	30	1	26	1.1	4700

AN APPROACH TO GEOTHERMAL DEVELOPMENT

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After about twenty years of geothermal energy development in New Zealand, progress is still hampered by incomplete knowledge. In some cases, this has led to unnecessary capital expenditure. Lack of accessibility of the medium and its complexity are major obstacles to achieving a better understanding, and the interpretation of field geophysical surveys is often tedious and may be open to ambiguity. There is no substitute for a properly logged drill-hole, with backup studies on the geology and geochemistry encountered, but exploratory drilling is expensive and often difficult to justify to an industry geared to "production psychology."

Most of the advances made in New Zealand have been achieved by compromise. Boreholes intended for production have been used as research holes during the drilling phase. Since production holes may be sited in quite dense clusters, a very detailed picture can be established within a geothermal field. Of course, the drawback to this approach is that few, if any, holes are available for study outside the field. This is an important gap in the geothermal information at the present time; it does not seem possible to determine precisely the volume of hot-water resource available without knowing the vertical temperature gradients at depth between the obviously active geothermal fields.

Where groundwater is abundant, with high water tables, geothermal activity is generally manifest at the surface. Thus the initial location of a resource may not be the main problem. It is necessary to map the resource and to determine how much energy is genuinely recoverable. Here the use of models can be of value. It has been found in New Zealand that the use of the experience gained in the detailed study of one field (Wairakei) can assist in modelling the performance of other fields in early stages of exploitation. Since all of these fields are within the same volcanic zone, it can be expected that their properties are reasonably similar.

However, the approach is not without pitfalls. Recently it was discovered that the Broadlands geothermal field, which appeared on resistivity studies to have a potential close to that of Wairakei, could perhaps be only partially exploited. During proving tests, the pressure drop encountered was found to correspond to a resource only about one-fifth the size of Wairakei (Grant, 1975). Two possible explanations for this have been considered. First, carbon dioxide levels at Broadlands are much higher than at Wairakei. When the pressure drops around a producing bore, it is possible that carbon dioxide comes out of solution to form a two-phase mixture with very poor transmissibility to water. The second possible explanation is that the poorly productive part of the field is not significantly faulted or fissured so that the bores are located in low-permeability media. If the latter explanation were valid, there would be some prospect for remedial action.

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In another example, the privately owned Kawerau geothermal field, which was thought to be of fairly minor significance, has now been shown to be highly productive from hydrothermally-altered graywacke below the surface volcanics. If this proves to be production from deeper horizons than were previously known, then the Kawerau resource could be upgraded substantially.

Geothermal research involves several disciplines; it can be perilous to neglect the contribution from any one of these. In Fig. 1, an attempt is made to indicate the inter-relationships between the fields which appear to have relevance in New Zealand geothermal research. Each heading is intended to be applicable both on the large (regional) scale and the local (geothermal field) scale.

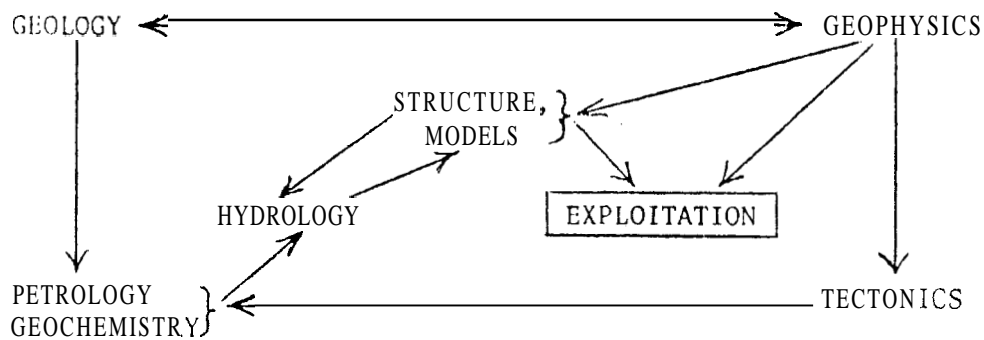


Figure 1. Aspects Relating to Geothermal Development

The large-scale geology and geophysics and associated tectonics are useful in describing the background under which high heat flows occur. Just what mechanisms are involved may have to be inferred from the petrology and geochemistry. This includes extensive use of isotope chemistry and dating methods. The term "hydrology"--here intended to embrace all aspects of fluid flow including hydrothermal convection--may be inferred from a knowledge of the field structure, including observed temperature distributions, permeabilities, and chemistry. Models are particularly useful in supplementing the available field knowledge, filling in the gaps by means of hypotheses, and leading to predictions which may be tested. If a model passes such tests, it may become a practical prediction tool. Many of the above aspects aid in the exploitation of a field, and the knowledge gained during exploitation provides essential feedback.

Models of Hydrothermal Systems

Resistivity mapping to a depth of about one-half kilometer has now been carried out by G. F. Risk and W. J. P. Macdonald of New Zealand's Department of Scientific and Industrial Research for a substantial part of the Taupo Volcanic Zone. Ample backup studies indicate that temperature maps would exhibit similar major features.

Unfortunately, detailed results of this quality are not obtainable in three dimensions using presently available geophysical methods. One line of models research is aimed at resolving the mechanisms of the groundwater convection problem and establishing realistic values for physical parameters of geothermal fields.

Just one aspect of this effort has been to determine meaningful values of field permeability. It is fairly clear that the large scale permeability of the field, which controls the major groundwater movement, is very low-- probably a little less than 10 millidarcies for vertical permeability. Some estimates for horizontal permeability have been significantly higher, but the value obtained from field draw-off studies is about the same as that in the vertical (McNabb, Grant and Robinson, 1975).

Modelling of field behavior under exploitation is of major importance. A successful fit has been achieved in the case of the Wairakei data using the formula

$$q = a + bp + c dp/dt \quad (1)$$

where q is the rate of draw-off, p is the pressure, t is time and a , b and c are coefficients which may be determined from the data. Fig. 2 illustrates a model (due to M. A. Grant) from which Equation (1) may be justified on theoretical grounds.

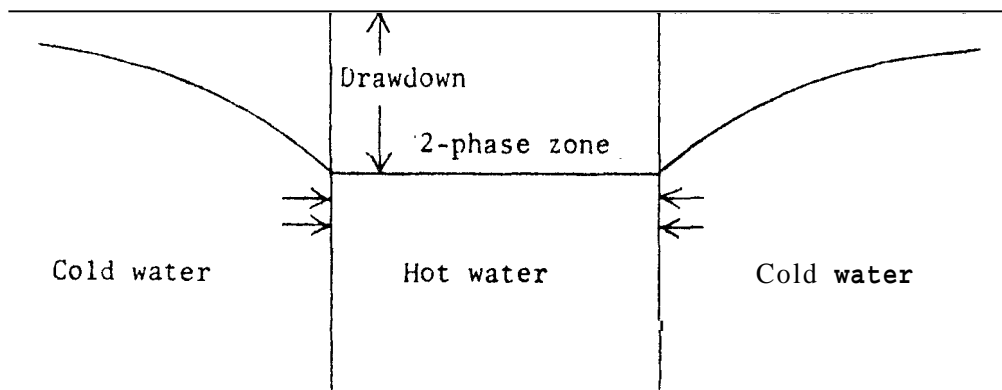


Figure 2. Model of Drawdown in a Hot-Water Geothermal Field (McNabb, Grant and Robinson, 1975)

In Equation (1), the term bp represents inflow from the sides, i.e., contraction of the hot zone, while $c dp/dt$ arises from drawdown of the water surface. The coefficient b depends upon the radius of the field. Since this contracts, b decreases slowly with time, but b may be treated as constant for small times. This indicates that, after draw-off begins, there is a rapid decay of field pressure, which asymptotes to an intermediate value. Further pressure decay is very slow, and is due mainly to contraction.

Equation (1) has been used, in particular, by Donaldson (1975), McNabb (1975), and it has been used for prediction of performance in the Broadlands geothermal field (Grant, 1975).

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GEOPRESSURED GEOTHERMAL RESERVOIR ENGINEERING RESEARCH
AT THE UNIVERSITY OF TEXAS

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To date, our research has consisted of designing reservoir simulators capable of modeling the behavior of geopressured geothermal reservoirs. The only model we currently have operational is a single phase (water) multi-dimensional simulator of such reservoirs. The model is a finite difference solution of the momentum transport equation for water. The model is two-dimensional, and either areal or cross-sectional studies can be run. The model allows for heterogeneous, anisotropic porous media. The effects of pore pressure reduction on fluid properties and reservoir parameters are included. Reservoir parameters include porosity, permeability, and formation thickness. Even though the presence of dissolved gas is not included in this model, its effects on momentum transport can be approximated by modifying the fluid compressibility.

We plan to use the model to examine the effects of rock compression and shale water influx on the performance of a well completed in a representative Gulf Coast geopressured geothermal reservoir. This will be done to aid in planning well design and production tests for an expected pilot well drilled into such a reservoir.

At this time, we visualize that a geopressured geothermal reservoir might appear like Fig. 1. A massive undercompacted sandstone body is bounded on the landward side by a growth fault. Seaward the formation grades into an undercompacted shale. At the top, the sandstone is bounded by a shale that allows no vertical movement of fluid. Below the sandstone there is an undercompacted shale. The fluid contained within the reservoir is a relatively fresh water. Hopefully, it is contaminated with natural gas in solution.

The sandstone body tends to be elongated in the direction parallel to the ancient seacoast. The body will be an ancient sandbar or delta made up of sediments deposited by the ancient rivers.

We feel the following phenomena will be important considerations in the development of reservoir simulators for the geopressured geothermal reservoirs:

Because of the depositional conditions, the reservoirs are heterogeneous. There is considerable evidence that shale water influx has played a role in the maintenance of reservoir pressures in gas wells completed in geopressured formations. The first attempts to examine shale water influx will be done by extending the modelled reservoir volume to include the off-shore shales. Both the shales and the sandstones will probably be anisotropic as well as heterogeneous.

Since the formations are undercompacted, as fluid is removed the reservoir will compact as the rock matrix assumes the overburden load. This compaction will provide a source of depletion energy for the reservoir. It will also reduce the cross-sectional area available for fluid movement and decrease the porosity and permeability of the formation.

The primary reservoir fluid is, of course, water. The temperature is expected to range from 300 to 400° F (150 to 200° C). The formations will be at about 14,000 feet (4,200 meters) in the Texas Gulf Coast. Therefore, hydrostatic conditions will be sufficient to keep the formation water in the liquid state during production.

The dissolved gas is an interesting complication. The mass of dissolved gas per unit mass of water is quite small at full saturation even at the elevated pressures and temperatures associated with geopressed reservoirs. If the formation water is fully saturated with natural gas, as soon as production begins this gas will evolve from the water. It is clear that total removal of the gas in solution will not result in a large gas saturation. The mobility of this gas coming out of solution is not known. For the purposes of reservoir simulation, the prudent approach appears to be to provide for the transport of the natural gas specie as either solution gas or as "free" gas.

If the reservoirs were simply to be depleted, the solution of the differential equations describing momentum transport for the formation fluids would be sufficient to model the behavior of geopressed geothermal reservoirs. However, it is certain that one of the exploitation schemes considered for such reservoirs will be the re-injection of the produced water into the reservoir after it has been "cooled" and "stripped" of the natural gas by the surface installation.

The re-injection of the "cooled" water makes it necessary to include the effects of thermal energy transport in the reservoir. We assume that the reservoir fluids and the rock matrix will be in thermal equilibrium. With reservoir temperature as a variable, fluid and rock properties will exhibit complex behavior.

The differential equations we feel describe the behavior of geopressed geothermal reservoirs are given as Appendix A at the end of this paper.

The boundary conditions for these equations deserve some comment. They will, of course, depend on the modeling study performed and the choice of the system to be represented.

At the top of the reservoir the vertical permeability of the shales will be extremely small. Over the productive life of the reservoir, fluid movement in or out of the reservoir can be neglected at this boundary. At the bottom of the reservoir there may be shale water influx. This can be handled in one of two ways. The most straightforward scheme would be to extend the reservoir system far enough into the shales that a specified potential or no-flow boundary might be specified. This will require a large computing grid. To reduce computer storage, it may be desirable to confine the computing grid to the sand body itself. In this case, the point source terms in the differential equations can be used to represent fluid influx. At the offshore boundary similar conditions can be applied. Along the growth fault, we expect that the boundary will be sealed. If production seems to indicate otherwise, we feel we can use the source terms to represent water influx. We anticipate handling the energy equation boundary conditions in a similar fashion.

APPENDIX A

DIFFERENTIAL EQUATIONS OF FLOW IN GEOPRESSURED GEOTHERMAL RESERVOIRS

Momentum Conservation

Water

$$\nabla \cdot \left[\frac{k_{rw} \bar{K} \rho_w}{\mu_w} \nabla (P_w - \rho_w gh) \right] + Q_w = \frac{\partial}{\partial t} (\phi S_w \rho_w) \quad (1)$$

Gas

$$\begin{aligned} \nabla \cdot \left[\frac{R_s k_{rw} \bar{K} \rho_w}{\mu_w} \nabla (P_w - \rho_w gh) \right] + \nabla \cdot \left[\frac{k_{rg} \bar{K} \rho_g}{\mu_g} \nabla (P_g - \rho_g gh) \right] \\ + Q_g = \frac{\partial}{\partial t} (\phi S_w \rho_w R_s + \phi \rho_g S_g) \end{aligned} \quad (2)$$

Energy Balance

$$\begin{aligned} -\nabla \cdot [\phi S_w \rho_w H_w \bar{U}_w + \phi S_g \rho_g H_g \bar{U}_g] + \nabla \cdot [\bar{K}_m \nabla T] \\ + Q_w H_w + Q_g H_g = \frac{\partial}{\partial t} (\phi S_g \rho_g H_g + \phi S_w \rho_w H_w + (1-\phi) \rho_r H_r) \end{aligned} \quad (3)$$

Variable Definitions

k_{rw}, k_{rg} = relative permeability to i^{th} phase.

$i = g$ (gas), $i = w$ (water), $i = r$ (rock)

\bar{K} = local rock permeability tensor

ρ_w, ρ_g = fluid density

μ_w, μ_g = fluid viscosity

P_w, P_g = pressure

g	= gravitational acceleration
h	= local elevation above a reference datum
Q_w, Q_g	= point source
ϕ	= porosity
S_w, S_g	= fraction of pore volume occupied by phase
R_s	= gas in solution per unit mass of water
H_w, H_g	= internal energy of i^{th} phase
U_w, U_g	= superficial (Darcy) velocity
a	= rock-fluid mixture thermal conductivity
T	□ rock-fluid temperature

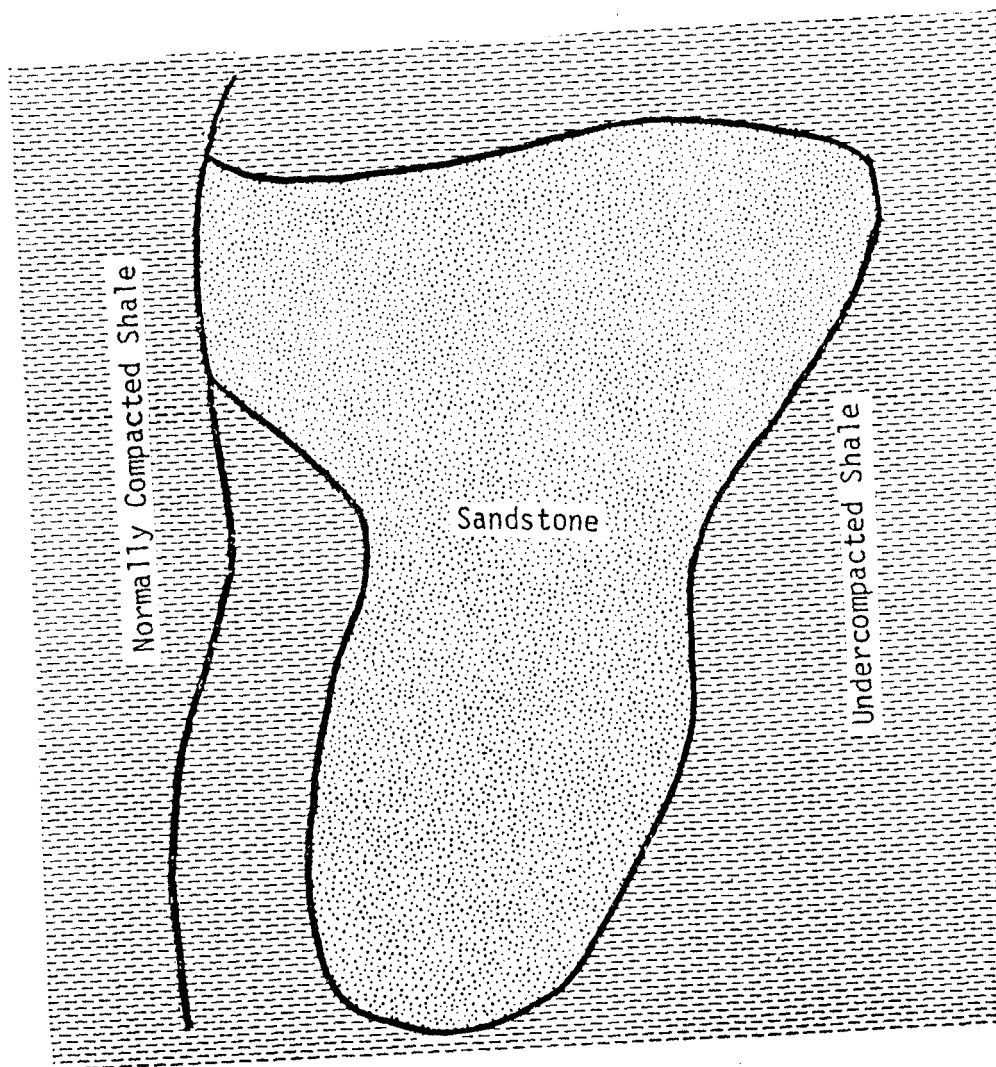
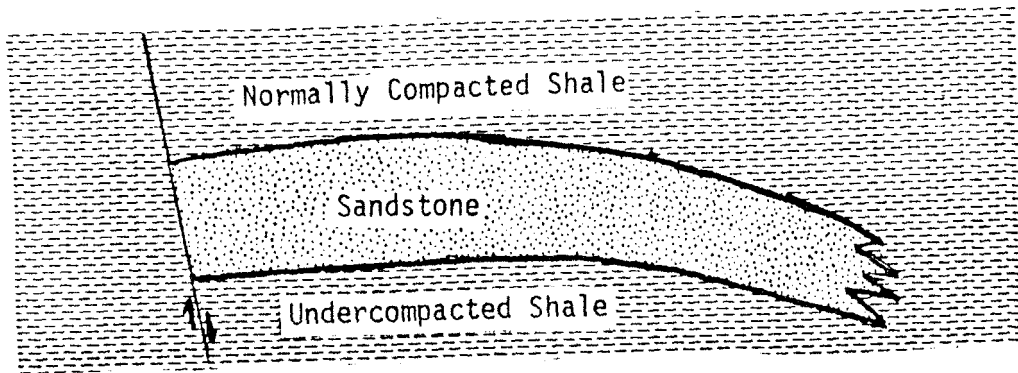


Figure 1 Cross-section and Plan View of Geopressured Reservoir

SDGEE PIONEERING GEOTHERMAL TEST WORK
IN THE IMPERIAL VALLEY OF SOUTHERN CALIFORNIA

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The San Diego Gas & Electric Company (SDGEE) is actively engaged in testing to develop methods to utilize geothermal resources at Niland and Heber in California's imperial Valley.

This paper describes San Diego's test program at the Niland area which is characterized by high temperature brines of high salinity.

San Diego's first testing began in April 1972. One production well was flowed at the Niland site for about ten days. The well flowed without pumping. Brine temperature and pressure at the production wellhead averaged 375°F and 150 psig. The geothermal brines which were produced were injected back into the reservoir through a 2,400 ft. deep well located about $\frac{1}{4}$ mile away.

The production of the well was, on the average, 400,000 lbs/hr. total mass flow. This was 324,000 lbs/hr of liquid (81%), 64,000 lbs/hr of steam (16%), and 12,000 lbs/hr of noncondensable gases (3%). The wellhead temperature and pressure remained stable at 375°F and 150 psig. The total dissolved solids averaged 225,000 parts per million and the indicated bottomhole temperature was 510°F at a depth of 2,250 feet.

Based on these tests, San Diego proceeded with a preliminary design of a Geothermal Test Facility. A direct steam turbine cycle was rejected because of the relatively high volume of noncondensable gases.

Field tests were carefully designed to simulate the phase separation and heat transfer conditions which would exist in the full-scale Geothermal Test Facility. The separator and heat exchangers used in these field tests were 1/20th scale versions of the proposed test facility equipment.

In the 1973 field test program, production of geothermal fluids from the well was held to a test flow of 20,000 lbs/hr. Brine, steam and non-condensable gases exited at the top of the separator and passed through the shell side of the steam heat exchanger. Brine, leaving the bottom of the separator, flowed through the tube side of the brine heat exchanger. The temperature of both the steam and the brine was 375°F. Distilled water was used for the heat exchange fluid. The dissolved solids in the geothermal brine flowing through the brine heat exchanger ranged from 200,000 to 245,000 parts per million. Dissolved solids in the steam at the exit of the test separator were 40,000 to 80,000 parts per million. Both the steam heat exchanger and brine heat exchanger heat transfer performance declined to unacceptable limits in about 100 hours of operation.

inspection of the brine heat exchanger tubes and header showed a scale buildup which averaged 0.060 inch thick. Amorphous deposits near the tube end were considerably thicker. The major constituents were silica (SiO_2 38%), iron sulfide (FeS_3 23%), and lead sulfide (PbS 11%). A layer of scale approximately .045 inch thick in the steam heat exchangers was attributed to the high carryover which was due to an undersized separator design and a lack of a scrubber downstream of the separator.

Scaling within pipelines which handled brine was another trouble area. A scale buildup one inch thick was observed in a pipe spool removed after six months of continuous brine handling service. The brine was exposed to air in the injection pump sump prior to pumping back into the reservoir. The brine process pipe was above ground and was not insulated to reduce heat loss.

Neither the mild carbon steel process piping nor the titanium heat exchanger tubing showed signs of corrosion during or after these tests. These findings were determined by metalographic inspection of the containment materials and chemical analysis of the scale.

We tested two methods of cleaning scale from heat exchanger tubes. Caustic solution cleaning proved to be more effective and faster than the hydrojetting method.

in March 1974, San Diego resumed field test work at the Niland geothermal field using scale models of a new design. The flow diagram for the test hardware is shown in Fig. 1. The flow of geothermal fluid from the producing well was controlled at a rate ranging from 50,000 to 100,000 lbs/hr at various times during the test program to map the separator performance. The geothermal fluids from the producing well entered the first stage separator at 150 psig and 370°F for this flow range. Approximately 5,000 to 12,000 lbs/hr of steam flowed out of the first stage separator to a scrubber where it was cleaned and then directed through the shell of the steam heat exchanger. The remaining brine flowed from the bottom of the first stage separator to the second stage separator which was operated at 50 psig. An average of 2,300 to 6,000 lbs/hr of steam flowed from the top of the second stage separator to the second scrubber where it was cleaned and then flowed through the tubes of the second stage heat exchanger.

Fig. 2 is a cutaway view of one of the separators showing the simple interior of the vessel. Both the first stage and second stage separators used in this test had the same configuration. Well fluid enters the separator at the port located in the bottom and impinges on the vessel end dome where a wearplate provides for protection of the vessel wall. Steam leaves the vessel through the upper port. Brine collects at the bottom of the vessel and flows to the second stage separator.

The test determined that a maximum liquid level of one quarter to one third of the separator diameter produced the most effective separation. The parameters found to be associated with this liquid level range are an inlet mass velocity not exceeding 50 feet per second, a steam velocity of no more than 5 feet per second and a separator length equal to approximately

four vessel diameters. Test results indicated approximately 100 to 200 parts per million of dissolved solids remained in the steam leaving both the first stage and second stage separators.

Fig. 3 shows the internals of the steam scrubbers used for the 1974 test program. Steam from the separator enters the scrubber through the lower port. It flows up through five trays which hold pure water obtained from the steam condensate at a point downstream from the heat exchangers. The water contacting the steam scrubs the solids entrained in the steam. Clean steam exits at the top, and the washwater, which is continuously added to the scrubber at a rate of 0.2 gallons per hour, enters at the top of the vessel. It cascades from tray to tray to the drain at the bottom and after leaving the scrubber is recombined with the brine stream and reinjected into the reservoir.

During the 1974 tests, the solids in the steam leaving the scrubbers were reduced to the level of 10 to 20 ppm, which is acceptable for steam heat exchanger operation.

The graphs in Fig. 4 show the results of the 1974 heat exchanger tests. The lines plot overall heat transfer coefficient for the first stage and second stage heat exchangers as a function of time of operation. The 1974 tests accumulated total operating time for the first stage heat exchangers of 398 hours. While the first stage heat exchanger was under test, an upset of operation in the scrubber occurred which resulted in a high carryover of dissolved solids from the scrubber into the first stage heat exchanger. This carryover was in excess of 3,000 ppm for a period of approximately 37 hours during the initial test operation. An extrapolation of the data indicates that, including the upset, the first stage heat exchangers would operate for about 3,200 hours before reaching design conditions requiring cleanup. Without the upset it is estimated this heat exchanger could operate up to a year before requiring cleaning.

A comparable analysis of the second stage steam heat exchangers indicates that they will operate for 10,000 hours before reaching design heat exchange conditions. Total actual operating time for the second stage heat exchangers was 587 hours.

The 1974 field tests at the Niland geothermal field demonstrated that the technology could be developed to handle the Niland brines for purposes of effective heat exchange. It also gave a good indication that a successful reinjection program can be accomplished at the Niland geothermal reservoir. At the start of the 1974 tests, the injected geothermal brine flow averaged 90,000 lbs/hr. at an average temperature of 165°F. Initially the injection pump discharge pressure required was nearly 400 psig, but after 16 hours of continuous pumping, the injection pressure dropped and brine flowed into the injection well by gravity. During the 6-month test program, injection by gravity flow could be maintained an average of six days before injection pressure gradually rose requiring another short period of pumping. The flow was varied between 60,000 and 120,000 lbs/hr. Temperature was maintained in a range between 150°F and 180°F by adding 10% irrigation water to cool the hot spent brine to prevent cavitation in the injection pump.

SDG&E directed the Ben Holt Company of Pasadena to proceed with engineering for a Geothermal Test Facility utilizing the multi-stage steam flash process with steam scrubbing and steam heat exchanger. This facility is the thermal loop portion of a 10 Mw binary electric generation plant. The isobutane turbine and associated generator set are simulated by an expansion valve in the isobutane loop. Fig. 5 is a flow diagram of the facility. This process does not make use of the brine in heat exchangers, but instead flashes the brine to steam in four stages to extract maximum heat. The condensate from the steam heat exchangers will be recombined with the remaining brine and the fluids reinjected to the reservoir through two wells.

In 1975 the U.S. Energy Research and Development Administration (ERDA) entered into a joint project agreement with San Diego Gas & Electric Co. for construction and operation of the 10 MWe sized geothermal loop experimental facility at Niland in the Imperial Valley. Under the agreement, costs will be shared 50-50 by SDGEE and ERDA. Estimated cost for the facility and experimental programs is approximately \$8 million.

SDGEE and ERDA plan for the completion of this facility in April 1976. Using two production and two injection wells, the operation of the Geothermal Test Facility should obtain essential data to confirm the design of the binary power cycle and to provide a first step in the determination of the Niland geothermal reservoir characteristics. SDGEE, ERDA, and others will continue to develop and test equipment as well as to establish required reservoir operating parameters and procedures. The goal of this program is to achieve the conversion of geothermal energy in the Imperial Valley to commercial electric energy.

1974 GEOTHERMAL FIELD TEST TWO-STAGE FLASH SYSTEM

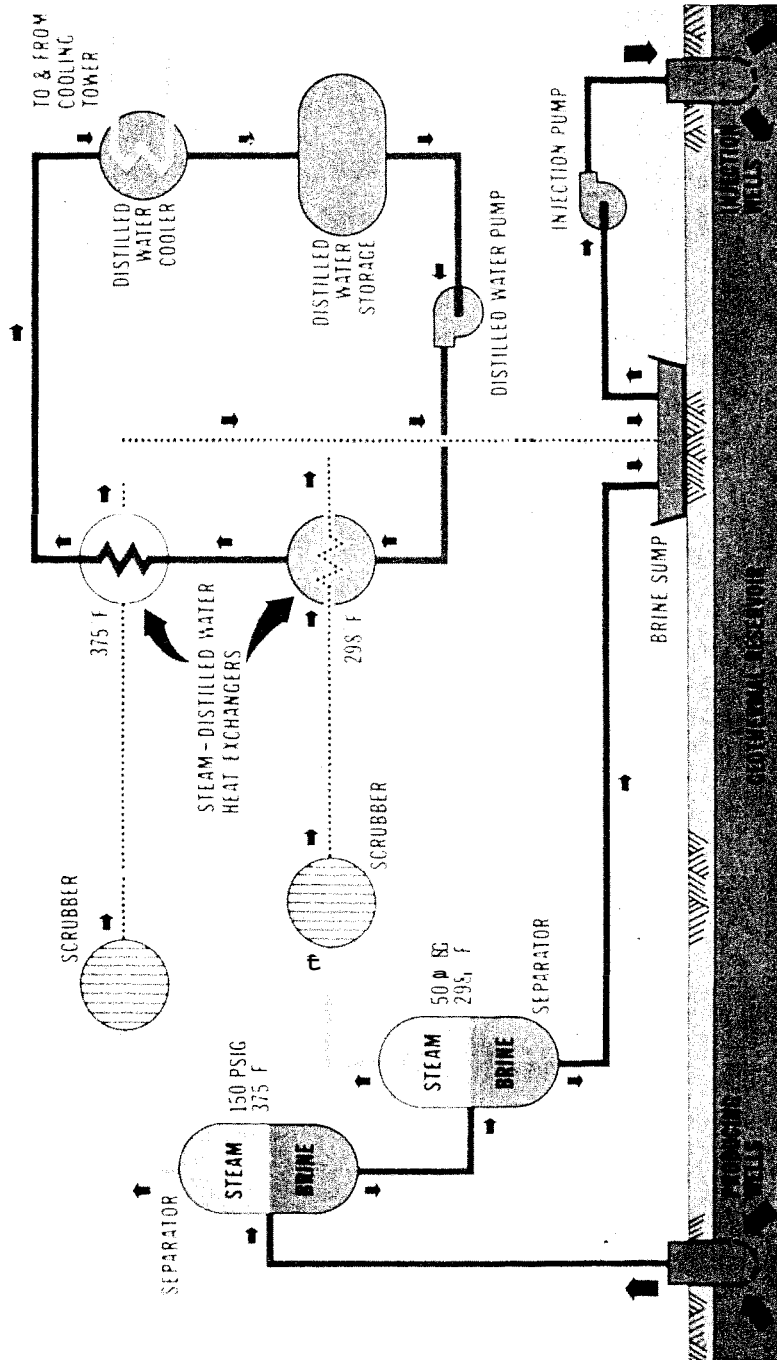


FIGURE 1.

C. F. BRAUN SCALE-MODEL SEPARATOR 1974 FIELD TEST

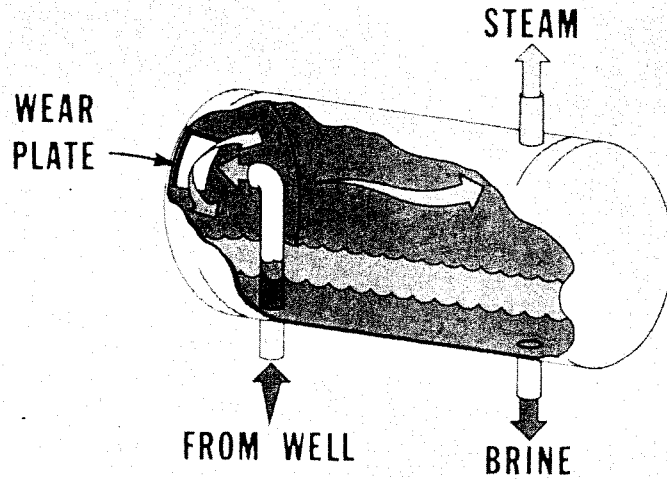


FIGURE 2.

BEN HOLT STEAM SCRUBBER 1974 FIELD TEST

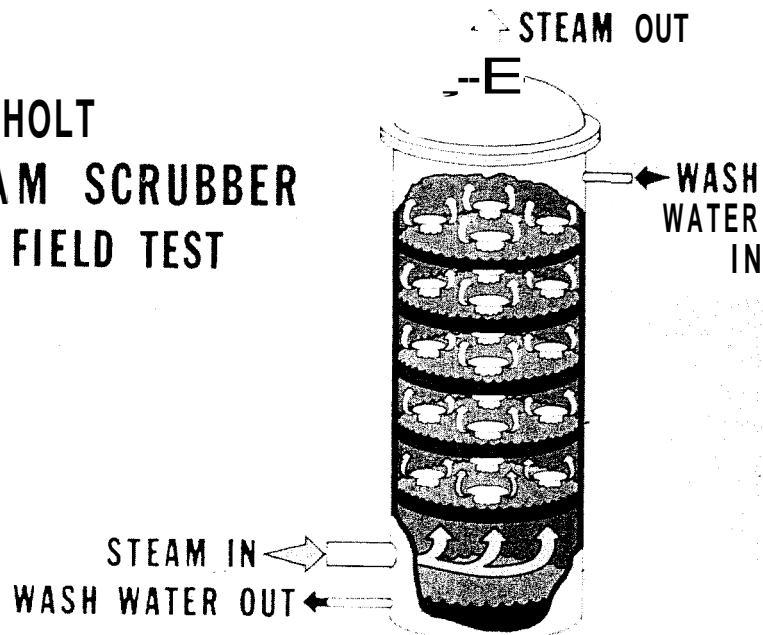


FIGURE 3.

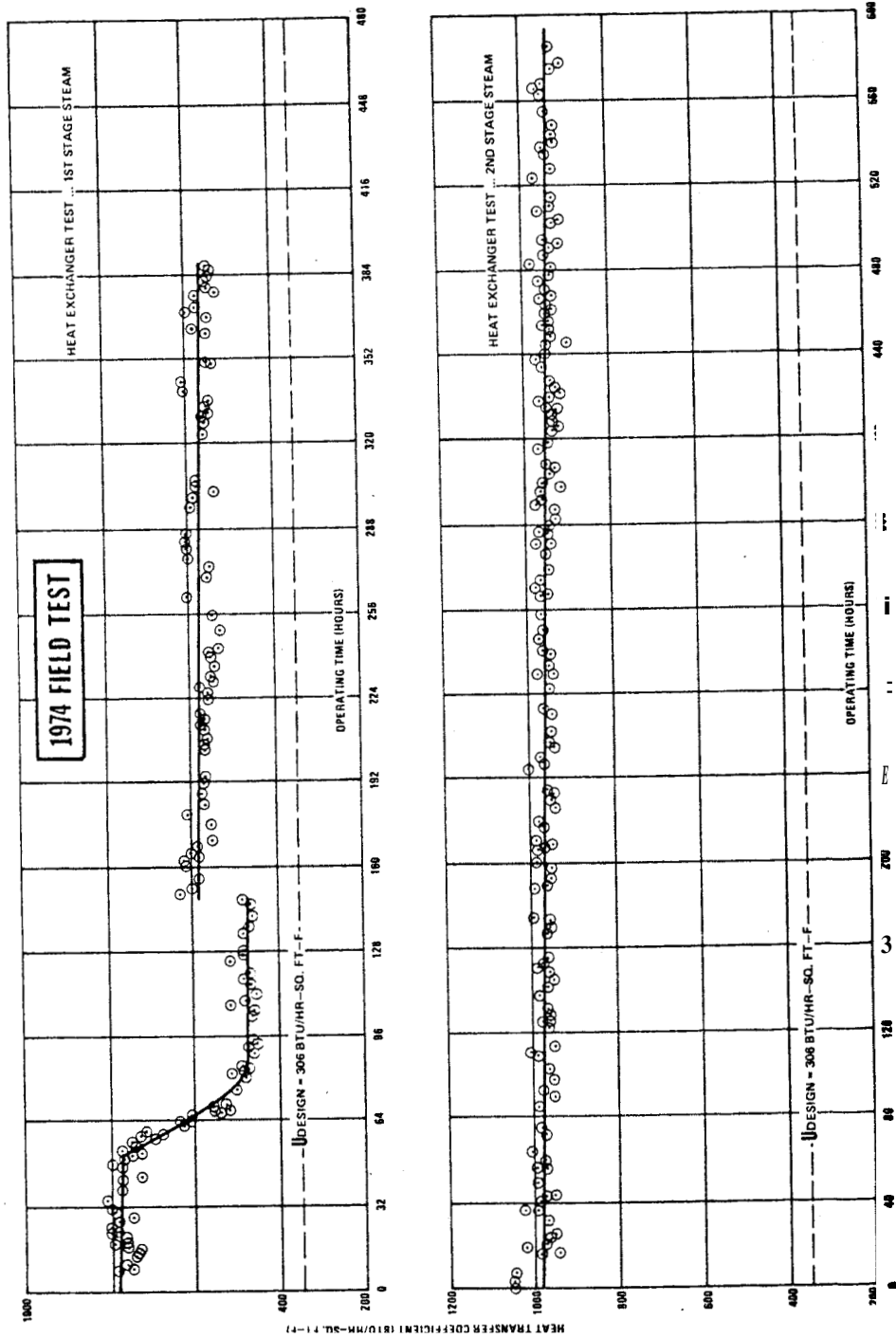


FIGURE 4

NILAND RESERVOIR MONITORING AND EVALUATION OPERATING PROGRAM

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Six wells will be utilized during operations to monitor reservoir parameters. Magmamax #1, Woolsey #1 and possibly later in the program Elmore #3 will be used for production. Magmamax #2 and #3 will be used for injection and Magmamax #4 and Elmore #3, initially, will be used for observation.

- I. Activities to be carried out prior to actual start-up of thermal test loop.
 - A. All wells will have temperature and pressure surveys taken.
 - B. Magmamax #3 will be flowed into a Baker tank to obtain baseline chemistry associated with the reservoir being produced from Magmamax #3. This information will not be an accurate determination of actual reservoir conditions in Magmamax #3 because considerable injected fluid has been put into Magmamax #3 in the various small scale testing operations carried on in the past; however, a baseline of existing brine chemistry in the vicinity of the reservoir which is penetrated by Magmamax #3 will be desirable for monitoring future injection operations.
 - C. Magmamax #2 will be flowed into a Baker tank at the minimum rate possible to clean the well out and obtain an accurate sample of the produced waters to establish a baseline prior to injection operations on brine chemistry. The anticipated duration will be one to two hours depending on flow capabilities and the tank holding capacity. Since Magmamax 2 has not been previously used for injection purposes a good sample of actual reservoir conditions should occur rather rapidly.
 - D. Magmamax #1 will be produced through the by-pass to the brine pit until evidence is shown that the well is producing at a stabilized rate. It may be necessary to shut down the well and pump the brine pit to Magmamax #3 several times before stabilization occurs.
 - E. Woolsey #1 will be produced on the same basis as Magmamax #1 until stabilization has occurred.
- II. Initial operations associated with the thermal test loop.
 - A. During the first three weeks Woolsey #1 and Magmamax #2 will be left in the shut-in condition and production into the thermal test loop will occur from Magmamax #1 at full production capable from that well and injection will be made into Magmamax #3. During this period of time pressure monitoring will be done on a continuance basis as

rapidly as the pressure monitoring device can be moved from well to well incorporating all six wells in the program. Pressure results will be logged and plotted daily to determine if any significant trends are established from this operation.

- B. A second three-week period will be carried out with Magmamax 1 shutin and Woolsey #1 producing into the thermal test unit and Magmamax 3 continuing as the injection well. The same program as far as observations go would be carried out for this mode.
- C. An analysis of the first six weeks of observation operations will be made to determine if both wells producing into the unit can be accommodated by injection into Magmamax #3. If this appears to be feasible then the continuing operating program would be to produce Woolsey #1 and Magmamax #1 into the thermal test loop and utilize Magmamax #3 for the total injection. During the initial six weeks of operation Schlumberger spinner surveys will be run in the injection well weekly and also if possible in the producing well. Analysis of the results of these surveys will determine the period for spinner surveys during the ongoing operation phase.

III. Ongoing operational phase.

- A. Observations of downhole pressures will be made every four hours during the ongoing operational phase. Spinner surveys and pressure buildup determinations will be made periodically based on the results found during the initial operational phase.
- B. Operational data will be transmitted to DeGolyer & MacNaughton weekly for analysis and interpretation and feedback from them will come forward with any suggestions as to additional operational requirements.
- C. When operational changes such as flow rates or pressures occur the monitoring of downhole pressures will be maintained at the most rapid rate possible until stabilization has occurred, and then the monitoring will go back to the four-hour periodic interval.

IV. General considerations.

- A. Much of the data accumulated relative to the brine chemistry and characteristics will be pertinent to both the SDGEE thermal test loop monitoring and the reservoir operations. Samples of the brine and steam in various locations of the thermal test loop would be taken periodically and analysis made to determine if there are any trends indicated in changes associated with the brine characteristics. Another feature which would be of prime importance is the monitoring of the quantities of noncondensable gases being produced throughout the duration of the testing operations. There is some evidence that the carbon dioxide may not be completely in solution with the brines in the reservoir and we may find a dropoff in carbon dioxide content after a certain amount of production. This will be monitored periodically to determine trends associated with carbon dioxide quantities being produced.

- B. From experience associated with the previous small scale testing at Niland and other locations such as Heber, Mammoth and Brady Hot Springs, there has been evidence indicating that the silica deposition occurs more rapidly as temperature levels are lowered. In order to acquire detailed information in regard to this, it will be desirable to start the initial operations with as high a temperature discharge to the injection system as possible which can be accommodated by the thermal test loop. With the design of the thermal test loop it is anticipated that silica deposition will likely occur in the brine portion of the flash vessels or in the injection piping or even into the injection well or the injected formation. Therefore it will be desirable to start with as high an injection temperature as possible and operate continuously for several days at that temperature, and after inspection operate with progressively lower temperatures on a periodic basis to gain information relative to the characteristics of the silica deposition problem. Pressure drops in the injection pipeline system and the injection well itself will be monitored to establish trends which can be indications of deposition in various locations in the injection system.
- C. Downhole pressure observations will be utilized to determine reservoir characteristics to establish potential barriers in the production zones of Magmamax 1 and Woolsey 1 and the injection zones associated with Magmamax #2 and Magmamax #3. This information will be continuously plotted with cumulated fluid production or injection as the abscissa and pressure as the ordinate. The information will be transmitted to DeGolyer & MacNaughton for analysis to establish reservoir characteristics. Magmamax #4 is completed above an identifiable shale in the reservoir and the injected fluid from Magmamax 3 will be going into the reservoir below this shale. Continuing pressure monitoring of Magmamax 4 will provide insight into the vertical permeability of the reservoir. Observations in Magmamax #4 may be also influence by production from Magmamax 1 and Woolsey #1 since the production zones of those two wells is in the same horizon as the open area into the reservoir perforated in Magmamax #4. Pressure observations will also be monitored in Elmore #3 to provide insight relative to effects on the reservoir associated with the production and injection operations, if any, at that location. Pressure shutin test will be made periodically as directed by DeGolyer & MacNaughton.

EAST MESA RESERVOIR

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INTERCOMP Resource Development and Engineering is currently working on contract to TRW Systems and the Bureau of Reclamation to provide petrophysical and reservoir engineering analysis of the East Mesa geothermal field. The twelve-month project was divided into three phases which consist of:

1. Analysis of current data and reservoir evaluation.
2. Design and execution of a long term flow test program.
3. Analysis of results and design of full scale reservoir development.

The first phase of the project is underway and portions of the work have been completed.

There are currently five wells drilled in the portion of the KGRA operated by the Bureau of Reclamation: 5-1, 6-1, 6-2, 8-1, 31-1. Each of these wells has a complete set of geophysical logs run and a SARABAND analysis by Schlumberger is available on a 1 ft. increment. In addition, core analysis was obtained from the 5-1 well in sufficient quantity to develop preliminary petrophysical transforms. Using the transforms developed in 5-1, INTERCOMP has performed a petrophysical analysis of the other wells to determine average reservoir properties over 250 ft. intervals. In particular, we determined ρ , h , k_v and k_h averages for each interval. To date there has been no geologic correlation established between any of the wells, so that property averaging by individual sand groups would not be meaningful.

This data will be used by TRW Systems to develop a geologic interpretation of areally distributed reservoir properties. These properties will then be used to compute the heat and mass in place within a selected areal contour for each interval. This will only give a refined estimate of the magnitude of the resource within the KGRA since actual data control is limited to the region near the wells. A substantial portion of the KGRA has not had deep wells drilled to date.

All of the flow test data taken to date is also being analyzed. INTERCOMP's 3-D Geothermal Wellbore-Reservoir model is being used to establish the effective flow properties of the system surrounding each well. Drawdown and/or buildup data is available on each well and shows that the reservoir exhibits complex flow behavior. We are investigating the possibilities that the flow can be represented as a dual porosity, fractured, or damaged system.

A 2-D model of the reservoir has **also** been developed using a 1000 ft. grid within the current drilled area. Using estimated properties, a sensitivity analysis is being performed in order to design an effective interference

test for the reservoir. We plan to develop a testing program that can be feasibly executed by the Bureau of Reclamation and that will yield sufficient data to determine effective reservoir performance characteristics between wells.

Fig. 1 shows a schematic of the KGRA with the heat flux contours and test grid. Fig. 2 shows a sample pressure map after 45 days of production from 6-1 at 600,000 lb/hr and reinjecting at the same rate in 5-1. The plot scale runs from 2400 to 2800 psia over the plot symbol range 0 through 10. In this case an aquifer of infinite extent has been attached to all edges of the grid. By varying rates, locations, and reservoir properties the sensitivity of reservoir to different testing plans can be determined.

The reservoir model will be calibrated to match the interference test data obtained from the field and an engineering design will be performed in the last phase of this project. In particular we will develop estimates for 1) resource lifetime, 2) well design and spacing, and 3) injection pumping requirements in accordance with operating characteristics and demands of surface facilities. TRW and INTERCOMP will be working with the Bureau of Reclamation to develop the operating plans on which each of these estimates will be based.

Reservoir Lifetime Estimate

The definition of "reservoir lifetime" is open to interpretation. However, the basic criteria used in this study will be a minimum allowable flowing wellhead temperature of 300°F. We will consider two basic cases in which the wells are produced by:

1. Submersible pumps which maintain single-phase flow in the wells.
2. Free flow in which the fluid will flash at some point in the wellbore. Two-phase flow in the wellbore will be accounted for above the flash point.

The calibrated reservoir-wellbore model will be used to predict the lifetime under the following delivery schedules:

1. Total flow of 10,000 lbm/min
2. Total flow of 100,000 lbm/min
3. Total flow of 1,000,000 lbm/min

There will be different lifetime estimates for each of these cases depending upon the spacing of production wells and location of reinjection wells.

Well Design and Spacing

From a reservoir engineering standpoint with water reinjection at the edge of the thermal area, this process is characterized as a "unit mobility waterflood." Under ideal conditions, the first cool water breakthrough will occur after roughly 70% of the original water is produced. After this Point, surface temperatures will gradually decline until the 300°F limit is reached. The total energy recovery depends upon the location of reinjection wells and therefore the total volume swept.

Maximizing energy recovery would at first appear to dictate reinjection as far from the thermal area as possible in order to sweep maximum water volume. However, the history match permeability distribution will dictate the allowable distance from the producing area in order to maintain pressure. Without adequate water recharge, the reservoir lifetime will be very short and dictated **solely** by reservoir pressure.

Similarly, drilling wells directionally from a single location for production would appear to minimize heat losses in the system. However, this usually results in a reduced well spacing. Under these conditions, the inner wells could interfere severely with the outer producing wells and therefore would be "starved." Again, the history match will determine the minimum allowable spacing for each of the proposed production schedules considering the environmental desirability drilling. The numerical model will be used in a trial and error fashion to establish this spacing.

Injection Well Pumping Requirements

For large scale developments the produced water must be reinjected into the producing zones in order to maintain reservoir pressure. This process, if designed properly, will also minimize any possible subsidence. The production-injection operation will set up a pressure gradient through the reservoir which will cause some subsidence within the producing area. If all of the produced water is recharged by reinjection the subsidence will be localized and small in magnitude.

The injection pumping requirements are strictly a function of the operating plans under consideration. For each plan there are three parameters which must be considered in order to evaluate the pumping requirements:

1. Location of reinjection wells,
2. Volumes reinjected per well,
3. Productivity index (PI) of each well.

The volume that must be reinjected is dependent upon the operating plan. The location of reinjection wells will be based upon the history match as discussed above. The productivity index can be estimated based on permeability, porosity and thickness at each particular reinjection location.

In addition to the above work at East Mesa, we are working with Republic Geothermal on their wells in the north end of the KGRA. We are assisting them in the evaluation of test results and the design of a testing program for the northern end. The results of this work are confidential and cannot be presented at this time.

GEOPRESSURED SYSTEMS

INTERCOMP is actively engaged in feasibility and geologic studies of geopressured geothermal systems. These systems contain substantial amounts of dissolved natural gas in addition to thermal energy. Fig. 3 shows that as much as 60 scf/Bbl of natural gas may be dissolved in these aquifers. The resource is generally located along the Texas-Louisiana Gulf Coast at depths of 12,000 to 15,000 feet.

The development of this resource is dependent on many factors, but the three most important are:

1. Is the fluid economically accessible?
2. Are the aquifers prolific enough?
3. Is the fluid technologically accessible?

We are currently conducting prospect evaluation and site selection studies in order to develop pilot projects that will help answer these questions. However, details of this work are confidential at this time.

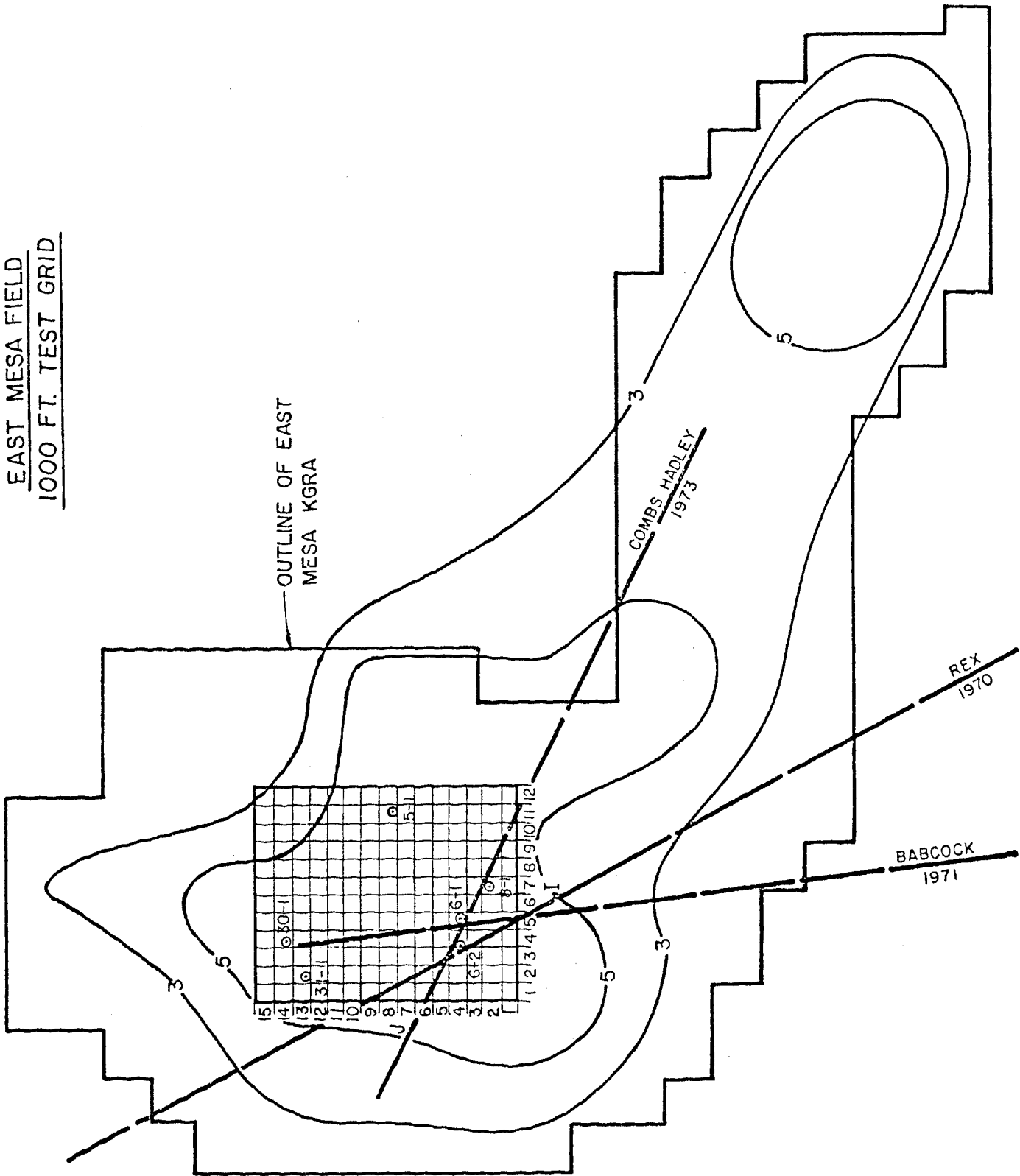
NUMERICAL MODELING

INTERCOMP has developed numerical models that are used in the engineering evaluation of geothermal systems. One model is a two-phase wellbore calculation. A second model consists of a 3-D reservoir model for single and two-phase flow in porous media with the wellbore model coupled in at the sand face.

Details on the first model have been published by Gould, "Vertical Two-Phase Steam-Water Flow in Geothermal Wells," JPT (Aug. 1974). Details on the second model were presented by Coats et al. "Three-Dimensional Simulation of Steamflooding," SPE 4500 (October, 1973). We are currently engaged in upgrading the flexibilities and engineering features of these models in order to meet current design requirements.

Figure 1

EAST MESA FIELD
1000 FT. TEST GRID



LABORATORY MEASUREMENT OF 98.7% METHANE GAS SOLUTION IN DISTILLED WATER (Culberson and McKetta, 1951)

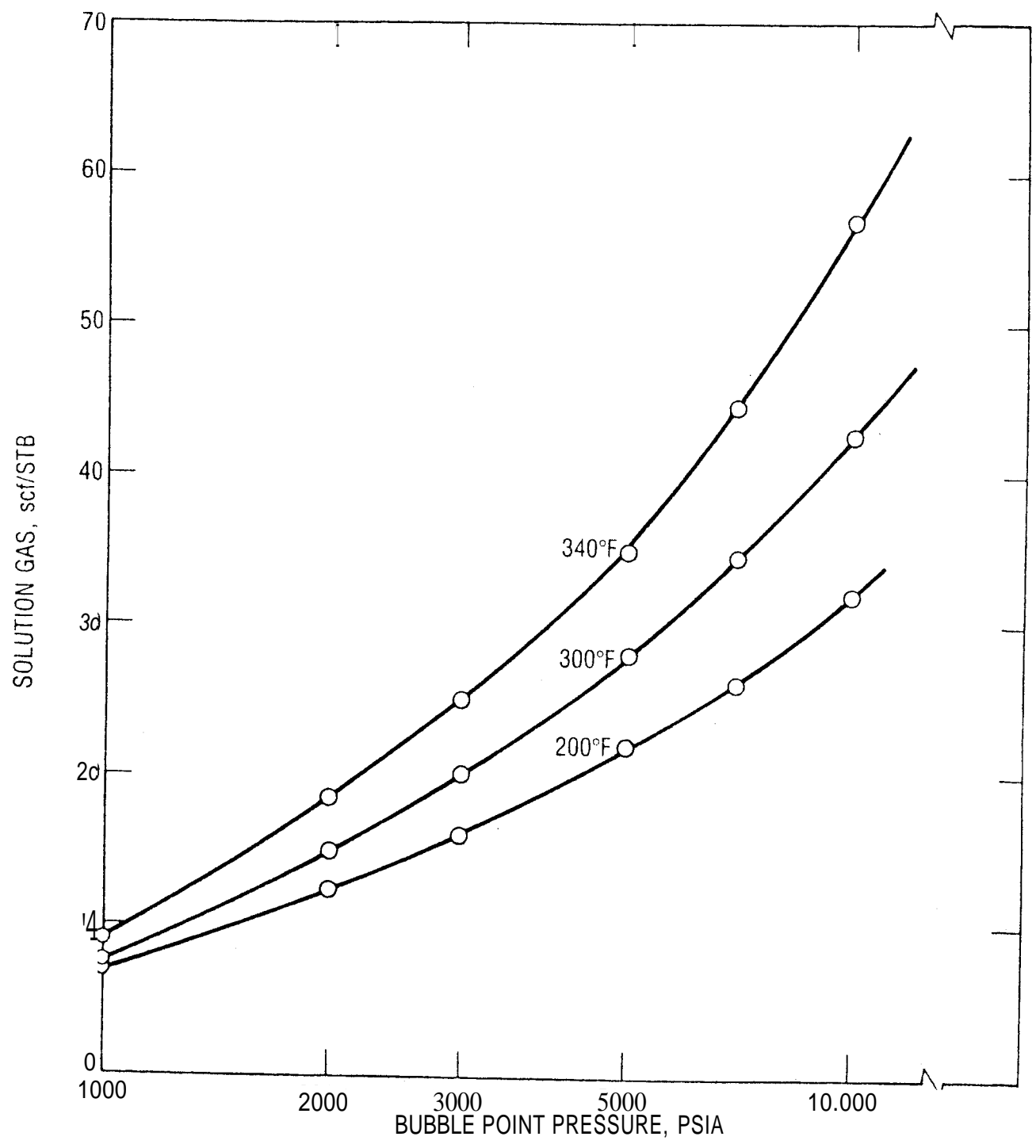


Figure 3.

THE PGandE GEYSERS POWER PLANT--A UTILITY COMPANY'S VIEWPOINT

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The existing generating capacity of The Geysers Power Plant constitutes about 5% of the total electric generating capacity of the PGandE system. The Geysers geothermal resource has and will continue to play an important role in our overall planning for generation additions. By 1979, four more units, Units 12 to 15, ranging in capacity from 55,000 kW to 135,000 kW, are planned to be in operation, almost doubling the capacity of The Geysers Power Plant to 908,000 kW.

Some PGandE Considerations as They Relate to the Steam Reservoir

Attached is our conceptual schedule of the time required for geothermal development, from the exploration phase through the power production phase. Geothermal steam as an energy resource is an economic alternative when compared with other forms of energy such as fossil and nuclear. PGandE continues to view geothermal development favorably; however, many of the issues and problems, etc., inherent in geothermal development affect the end-user of steam as well as the developer of the resource.

PGandE, as a utility that is regulated by the CPUC, the new ERC&DC, FPC and others, is somewhat different from a steam developer. PGandE is responsible for taking reasonable steps to provide adequate firm electric power to its customers at reasonable rates. In discharging this responsibility, the Company must of course act within all the applicable environmental, economic, and legal restraints that exist for utilities in California today. Because the steam developers are willing and able to produce adequate quantities of steam, and market it at reasonable rates, PGandE has not participated in exploration and development of the steam resources.

In accordance with current ratemaking, and operating experience, PGandE amortizes its investment in a generating unit and in related electric transmission facilities over about a 30 to 35-year period. Adequate reservoir information is required prior to the commitment of major expenditures for a power plant in order to assure that the reservoir will supply steam over the life of the using facility.

PGandE presently has steam supply contracts with Union Oil Company-Magma Power Company-Thermal Power Company, Pacific Energy Corporation, and Burmah Oil and Gas Company. An important feature of all our steam supply contracts is that PGandE and the suppliers agree to accept reservoir engineering data as a basis for estimating the ability of The Geysers steam field to deliver steam over a long period of time. Many of you are no doubt aware that PGandE has been and continues to be grateful for the assistance of the reservoir engineering discipline, especially here at Stanford University, in the development of guidelines and procedures that are used in evaluating the geothermal reservoir.

Our contracts also provide that as additional steam reserves are proved, PGandE will install additional generating units. Our present resource program calls for approximately 100,000 kW per year. The additional reserves are proved by both successful stepout drilling and study of production history of existing wells. We anticipate that we can beneficially utilize any or all of firmly available geothermal steam that can be proved by steam developers in The Geysers area in the foreseeable future.

Status of H₂S Abatement at The Geysers

Anyone even remotely familiar with The Geysers development must be aware that H₂S emissions have been one of the major factors causing the current reduced rate of development. Because some of you are associated with companies which may get into geothermal development at The Geysers, let me take a minute or so to briefly describe the status of the H₂S abatement efforts now underway.

The hydrogen sulfide in the geothermal steam is presently released from the power plant in two ways. The larger portion of it dissolves in the cooling water in the direct contact condenser and is then stripped out in the cooling tower. The remainder is removed along with other noncondensable gases by the condenser off-gas removal equipment, and is discharged into the atmosphere.

One abatement system PGandE developed is the catalytic iron oxidation method, now in operation at Unit 11. It effectively reduces emissions from both the condenser vent gases and cooling tower emission sources. This process works to reduce releases from the cooling tower by addition of an iron sulfate catalyst to the cooling waters. This catalyst causes the oxidation of hydrogen sulfide to elemental sulfur. The process has been demonstrated to work very well in removing H₂S from the cooling tower emissions; however this method appears to cause accelerated corrosion of unit components which in turn can reduce unit reliability and thus the amount of steam we can accept from the producers. Also, this process produces a sulfur sludge that is not saleable or reclaimable, and must be disposed of in a specially-approved land fill site.

Another system, which we call the "burner scrubber" technique, is under test at Unit 4. The condenser off-gases, which contain enough methane and hydrogen in addition to hydrogen sulfide to be combustible, are burned. This results in sulfur dioxide which is scrubbed in the cooling waters.

For future units (starting with Unit 12), we plan to use the Stretford system in conjunction with a surface condenser. This is a chemical system which reduces the H₂S to elemental sulfur.

PGandE's Concern with Certain Federal Leasing Regulations

As a user of geothermal steam for electric generation, PGandE is concerned over several elements of the federal Geothermal Leasing Regulations. One concern is the requirement that certain terms of federal leases

be renegotiated 10 years after the first commercial steam is produced. Since capital investment in geothermal generating facilities is amortized over a 30- to 35-year period, this provision in the leasing regulations places some doubt upon the wisdom of investing large capital sums in building such facilities when the steam supply is not assured over a comparable period of time.

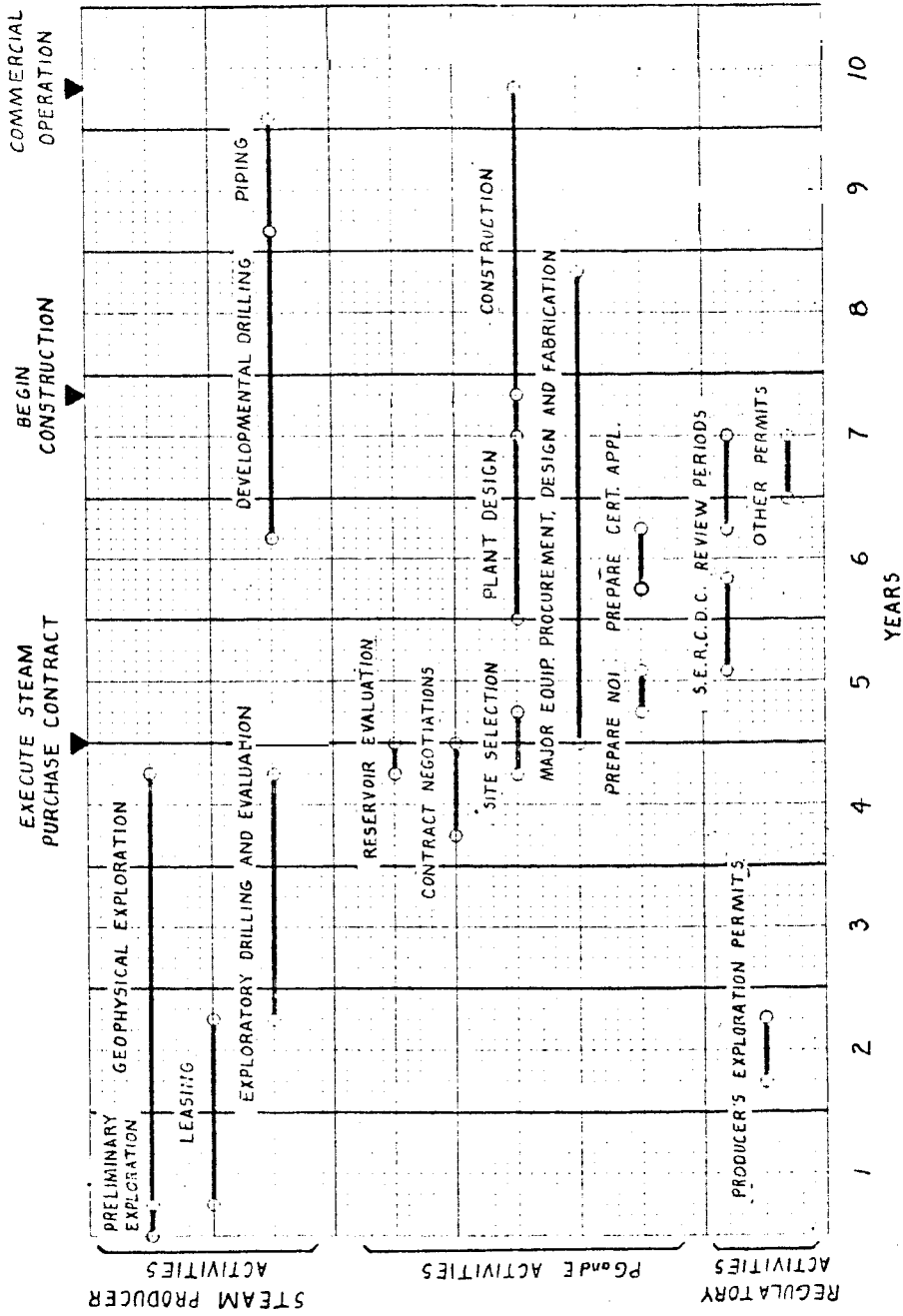
Another element of concern is the provision that a lease "supervisor" is given the authority to close down, without giving notice or hearing, an entire geothermal operation which he considers to be unsafe or which could cause pollution. This unilateral authority given to one individual also places doubt upon the wisdom of making large capital investments in these facilities.

A third concern is about the uncertainties that are raised by the gratuitous insertion in the federal leases of a provision, not required by the leasing regulations, reserving to the government the right to issue orders necessary to "insure the sale of the production from the leased lands at reasonable prices, to prevent monopoly, and to safeguard the public interest." What this reservation does for security of tenure and long-term assurance of the right to operate, deliver, and use a geothermal resource is unknown.

Conclusion

To sum up, PGandE believes that existing and future geothermal development at The Geysers has and will make an important contribution as a source of electric energy. I have briefly described some problem areas of both a technical and institutional nature that we think can be satisfactorily resolved if all of us in the geothermal industry continue to apply the necessary combination of creativity and effort. The reservoir engineering aspects of the project have played a significant role in the development of this important resource and we look forward to the continuation of the work being described by the participants of this workshop to enhance our understanding of the resource so that its development can advance in a manner that produces benefits for the developers, users and society at large.

TYPICAL SCHEDULE FOR THE GEYSERS DEVELOPMENT



GEOTHERMAL RESERVOIR PRESSURE REQUIREMENTS FOR PRODUCTION

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Rogers is an engineering company, and as such our interest in reservoir engineering is concerned with the production aspect. Reservoir testing and production management techniques practiced today are largely rule-of-thumb. We are hoping to learn from you such parameters as proper well spacing and wellbore sizing for a given reservoir which will provide optimum production and life of the reservoir. We cannot contribute much in this area other than perhaps to ask the questions which may stimulate research and to relate some of our observations as to what we find is required to satisfy our needs. For example, in making reservoir modeling studies we feel it is very important that the chemistry of the system be considered, particularly where it is indicated that production will be affected by flashing in the reservoir.

There have been instances where well production has been limited by reservoir permeability rather than by wellbore diameter. When such wells are produced to their maximum capacity, the pressure drawdown in the reservoir exceeds the gas evolution pressure, and flashing occurs in the reservoir. If the reservoirs are in shale or limestone (carbonate) formations, calcite precipitations can occur at the point of flashing. Well flow may cease entirely due to loss in permeability. This situation has occurred in some of the wells drilled in Casa Diablo. Flashing in the formation could have been prevented by operating the wells at a higher back pressure, but this would have reduced the well flow to uneconomic production rates.

The wells in Kizildere, Turkey, have high fracture permeability, so they can be produced at high rates without flashing in the reservoir. Flashing occurs in the wellbore, and calcite precipitation and plugging occur there and in the surface equipment.

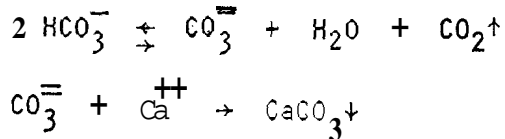
By installing a pump in the well, the point of flashing can be moved downstream of the wellbore and even the surface equipment, e.g., the heat exchangers of a binary cycle plant, but I do not think it possible to prevent flashing entirely because of the noncondensable gases dissolved in the geothermal water. The amount of noncondensable gases dissolved in geothermal brines varies from well to well, but most brines contain enough gases such that they will flash off even if the brines are cooled to below the atmospheric saturation pressure. Taking the KD-14 well for example, the discharge pressure of the pump would have to be high enough to hold 520 psig through the heat exchangers in order to hold the noncondensable gases in solution, while it would only take 230 psig to prevent steam flashing.

The pressure downstream of the 520 psig back pressure valve would be determined by the reinjection well pressure in a totally enclosed system. Reinjection well pressure requirements have been shown to be quite nominal in those situations in which it has been tried, so there would be a significant pressure drop across the back pressure valve. The noncondensable gases

would evolve, and if they were not vented, the reinjection well would become "gas-bound." Therefore, I believe it will be an exceptional case if a binary cycle plant can be operated totally enclosed. The environmental pollution advantages claimed for the closed binary cycle plant therefore will not be realized.

The concept of using downhole pumps to prevent flashing by maintaining total required pressure on the system is an expensive one, not only in terms of the complex mechanical pump which must operate in a hot corrosive environment, but also from the higher pressures for which the power plant exchangers would have to be designed.

We have taken another approach to the problem which we believe will be more reliable and less expensive to operate. Our system permits the well to produce fluids by steam flashing in the wellbore, but we prevent calcite precipitation by recycling carbon dioxide gas down the wellbore in sufficient quantity to maintain the carbon dioxide partial pressure in the system and maintain the carbonates in the soluble bicarbonate form.



The adaptation of the recycle CO₂ system to the binary cycle is shown in Sketch No. 3. The capital and operating costs for this system are less than those for a pumping system utilizing long shaft well pumps. Maintenance costs should also be less because there are no moving, mechanical parts in the hot, corrosive environment of the wellbore.

Whether by pump or by the CO₂ recycle system, the control of calcite precipitation, we believe, will also control the silica laydown problem. We have run limited field tests which suggest that precipitated silica is cemented together by the precipitation of calcium carbonate.

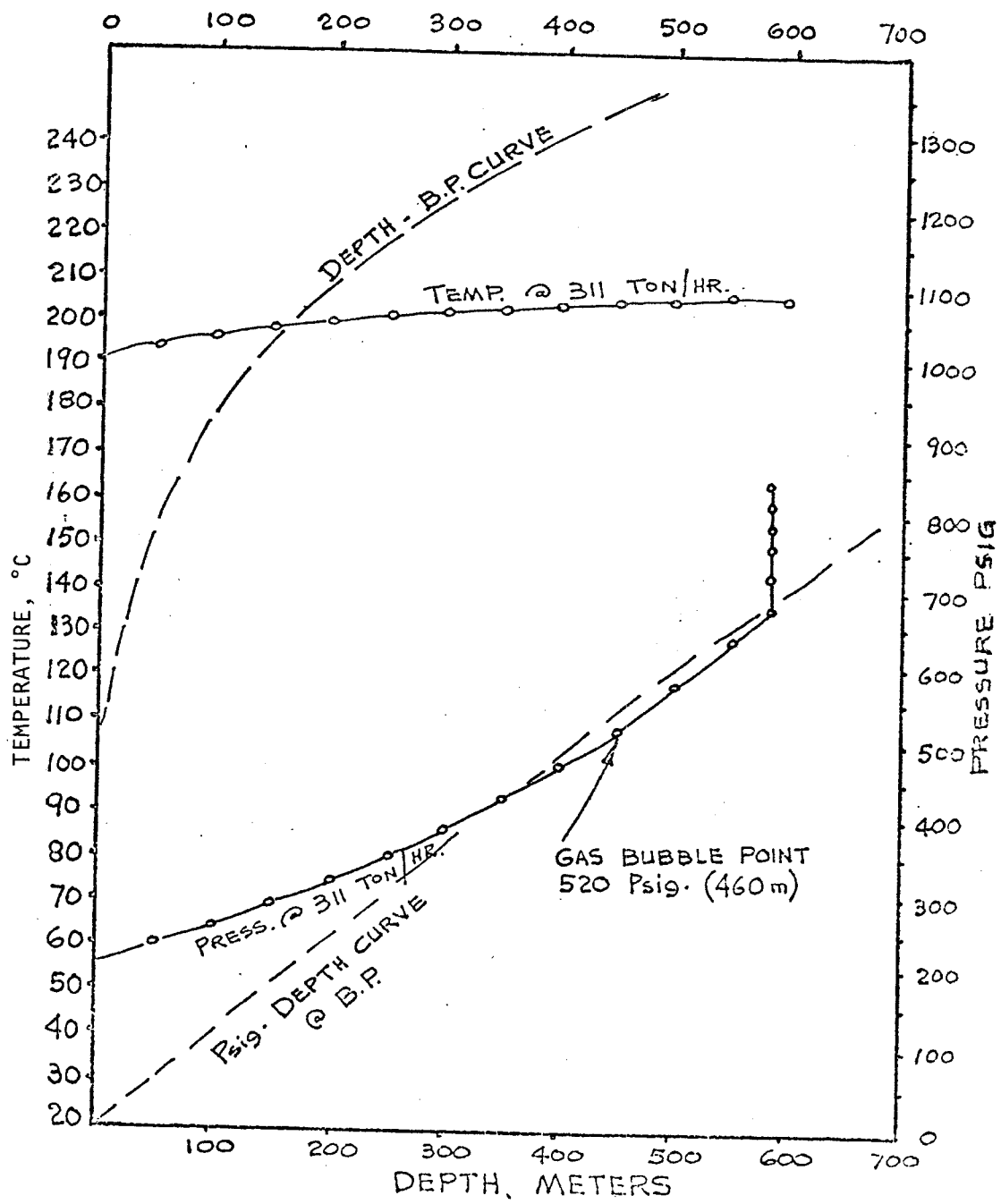


FIGURE 1.

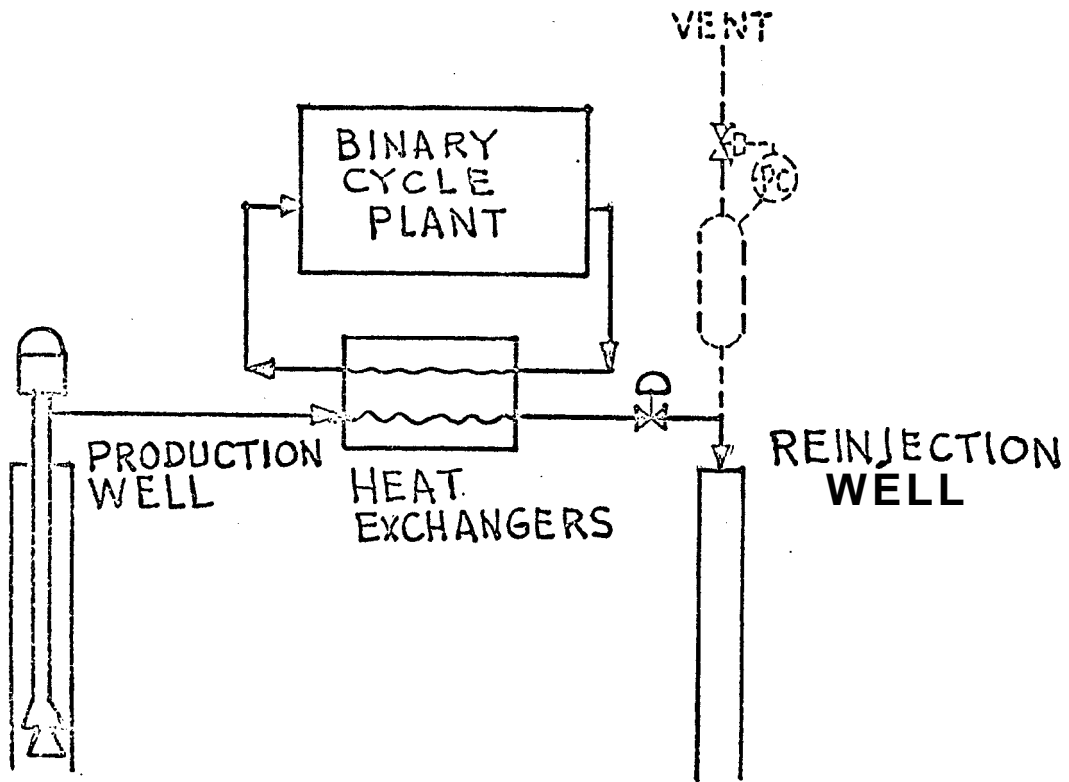


FIGURE 2.

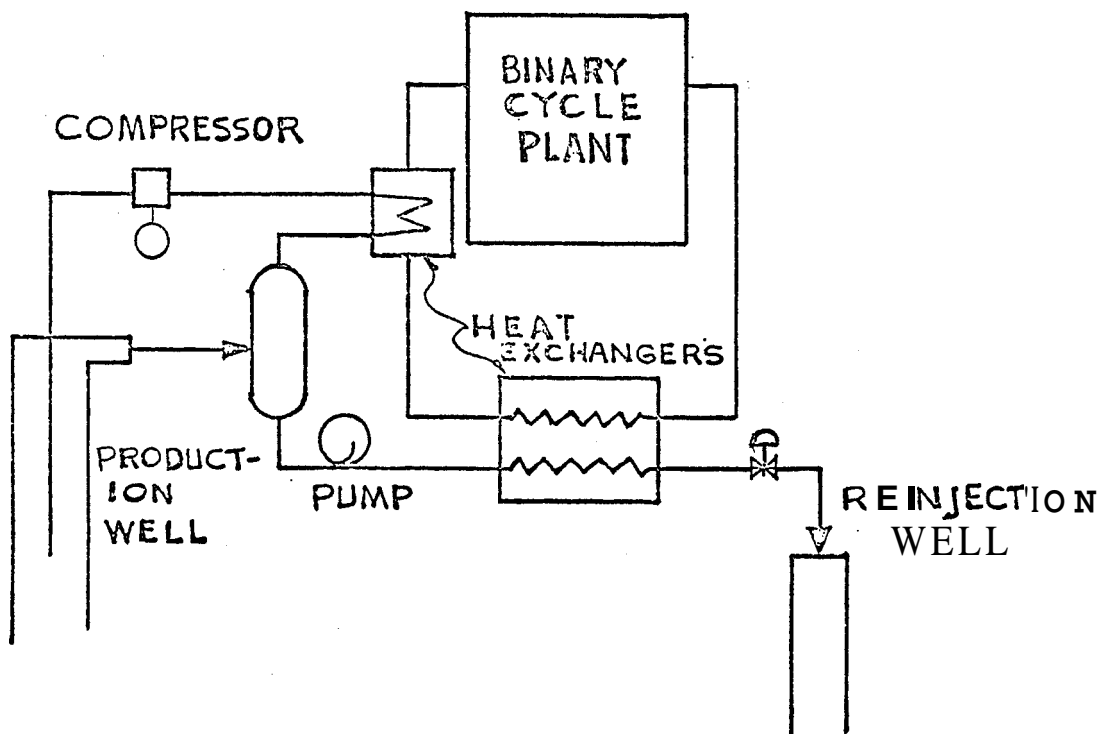


FIGURE 3.

ON THE OPTIMAL RATE OF GEOTHERMAL ENERGY EXTRACTION

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A geothermal reservoir is, among other things, a stock of heat energy of a given "quality," stored in an aquifer system. In this study, the stock is considered finite and exhaustible over the relevant economic horizon. An important consideration in exploiting this resource is the "optimal" rate at which the energy stock should be extracted from a particular geothermal anomaly. This is primarily an "economic" question, although any meaningful conclusions on an optimal extraction policy must surely be based on a specific model of the physical hydrothermal processes that occur in the geothermal aquifer. Accordingly, the purpose of this paper is to outline some economic models for optimal extraction, in the context of a particular hydrothermal model.

The discussion focuses on one anomaly. The rate of hydraulic pumping is the major decision variable, and the analysis trades off discounted "value" of energy from the anomaly against the rate of deterioration of the quality (temperature) of the heat stock. All extracted fluid is recycled, and no divergence between private and social benefits and costs is assumed. Secondary or indirect regional benefits and costs associated with development are not considered.

Two economic models are developed. The first is "quasi-steady-state," in that the flow rate, Q , of fluid extraction is constant over all relevant time, although the temperature, T_o , of the extracted fluid varies with time. The second is completely "non-steady-state," assuming both Q and T_o vary with time. A major objective of these notes is to state, as clearly as possible, the major assumption of these economic models, so the appropriateness of hydrothermal model selection can be evaluated by physical model researchers.

The Hydrothermal Model

The hydrothermal model adopted for this discussion was developed by Gringarten and Sauty. It assumes a pumped production well for a single phase (hot water) geothermal anomaly with a recharge well as shown in Fig. 1 (actually each well could represent a cluster of wells).

Fluid is withdrawn at the rate Q (cfs) and recharged at the same rate. The temperature of extracted fluid at time t is T_o^t , and recharged fluid enters the ground at temperature T_i in period t . T_i is the temperature of condensed exhausted steam (on the cool side of the turbine). It is determined by turbine design and does not vary with time. When the temperature of the aquifer matrix has dropped to T_i , no more energy may be extracted.

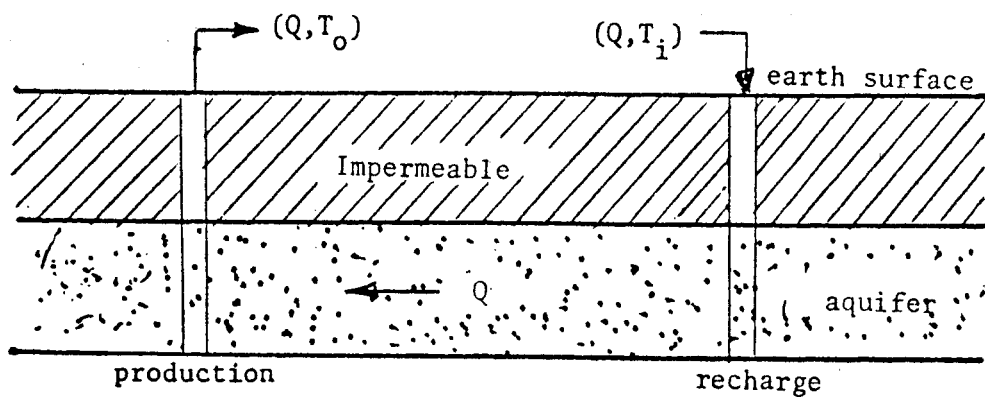


Figure 1

The recirculated fluid is heated by the aquifer matrix from T_i to T_o . For the first τ years, ($0 \leq t \leq \tau$), $T_o^t = T_o^o$, where T_o^o is the initial equilibrium temperature of the unexploited anomaly. The magnitude of τ is inversely proportional to Q :

$$\tau = f(1/Q).$$

The symbol τ denotes time until reduced fluid temperature "breaks through" to the production well.

After the τ^{th} year, T_o^t drops exponentially toward T_i at a rate $g(Q)$, as shown in Fig. 2. In general, T_o^t can be written:

$$T_o^t = \left\{ \begin{array}{ll} T_o^o & 0 \leq t \leq \tau \\ T_i + (T_o^o - T_i)e^{-g(Q)(t-\tau)} & \tau < t \end{array} \right\}$$

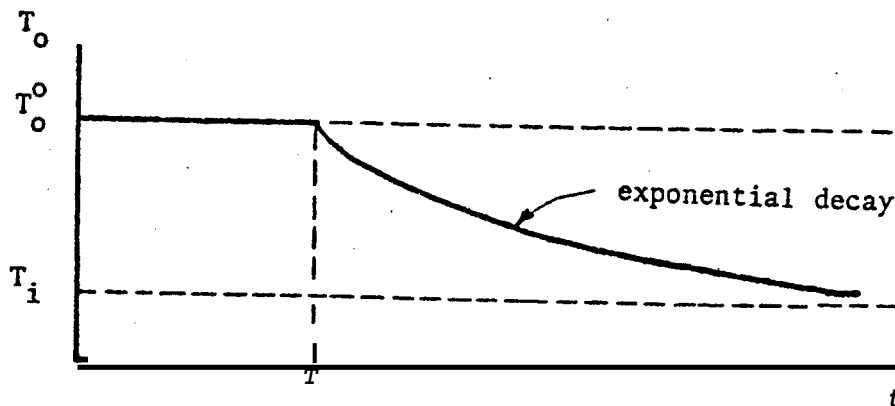


Figure 2

The functions f and g are derived using results of the hydrothermal model.

The system is assumed base loaded into a local power grid. The base load energy, $E(\text{kwhr})$, available from the process is proportional to the product of Q and $(T_0^t - T_i)^{\frac{1}{2}}$: $E^t = h(Q(T_0^t - T_i)^{\frac{1}{2}})$

The value of E is determined by the "long-run" value to the grid of a kwhr of base load energy ("long-run" implies grid power system capacity as well as operating costs). This value is the price the power company is just willing to pay for marginal units of baseload power. If we denote this value as a function of time, $p(t)$, we have:

$$p(t) \sim p^0 e^{rt},$$

where

p^0 = price at $t = 0$.

r = rate of increase of baseload power system costs relative to general price level (in other words, we are dealing in "real" dollars throughout all time).

The costs associated with extraction depend on Q , T_0^0 and T_i . Capacity (investment) costs will be incurred for drilling, lining of both holes, piping, pumps, and turbine-generator equipment. After L years, salvage costs are zero, where L equals life of equipment. Operating costs will depend on Q and an downhole pressure, which is related to T_i . Rate Q will determine pump capacity and turbine costs, while pressure will affect pumping energy requirements. Let $C(Q, T_0^0, T_i)$ be present worth of all capacity costs (which are incurred at $t = 0$) and operating costs. The discount rate will be i , and we say a (real) dollar at time $t = j$ has present worth of e^{-ij} at time $t = 0$.

The "Quasi-Steady-State" Model

The "Quasi-steady-state" model assumes Q is constant over a finite horizon, N , where N is an integer multiple, k , of L , the life of turbine-generator equipment. For the case where $k=1$, $\pi_1(Q)$, the total discounted net revenue from the system over the first L years, when pumping occurs at rate Q , may be written as:

$$\begin{aligned} \pi(Q) = & \int_0^{T=f(\frac{1}{Q})} p(t)h\left(Q \cdot (T_0^0 - T_i)^{\frac{1}{2}}\right) e^{-it} dt \\ & + \int_{T=f(\frac{1}{Q})}^L p(t)h\left(Q \cdot (T_0^0 - T_i)^{\frac{1}{2}} e^{-g(Q)(t-T)}\right) e^{-it} dt \\ & - C(Q, T_0^0, T_i). \end{aligned}$$

When the integrals are evaluated, the resulting function can be optimized over the pertinent range of Q:

$$\pi_1^*(Q) = \max_Q \pi_1(Q)$$

$$\text{s. t. } Q \geq 0.$$

In general, we can repeat this optimization for $k=2,3,\dots$, obtaining $\pi_2^*(Q_2^*)$, $\pi_3^*(Q_3^*)$, etc. Then for some k^* ,

$$\pi_{k^*}^*(Q_{k^*}^*) \geq \pi_\ell^*(Q_\ell^*) \quad , \quad \ell = 1,2,3,\dots,$$

and $N^* + (k^*)L$ is the optimal horizon.

Although this "quasi-steady-state" approach considers horizons of indefinite length, it is somewhat restricted, in that Q is assumed constant for all time. A more flexible approach would allow Q to vary from year to year.

The Non-Steady-State Model

If the restriction on constant Q is relaxed, an investment timing dimension is added to the economic model. An extraction policy is then defined in terms of a vector of pumping rates:

$$\bar{Q} = \{Q_1, Q_2, \dots, Q_N\} \quad ,$$

where Q_t is the pumping rate in the t^{th} year. An optimal policy, \bar{Q}^* , is a policy that maximizes the pertinent objective function, namely, discounted net revenues. We are now considering the optimal "staged" development of an anomaly.

The same hydrothermal model is assumed. However, the big difference is that the fluid pumping rate, Q, can be increased in any year (at some incremental investment and operating cost). The goal now is to find not one Q, but a set of Q's, an investment-pumping policy that maximizes discounted net revenues.

To do this we define system state variables, Q_N and T_O^N .

Let:

Q_N = fluid pumping rate from extraction well just before beginning of period N.

T_O^N = temperature of extracted fluid just before beginning of period N.

$V_N^*(Q_N, T_O^N)$ = The optimal "value" of being in state (Q_N, T_O^N) at beginning of period N. This is the present worth (as of beginning of period N) of sum of net revenues in period N, N+1, N+2, ..., assuming an optimum policy is followed; that is, the sum of these net revenues discounted to beginning of period N is equal to $V_N^*(Q_N, T_O^N)$.

Now suppose that $N = 100$ and the discount rate is large enough so that the present worth in year zero of $V_{N+1}^*(Q_{N+1}, T_o^{N+1})$ is zero. Then this is tantamount to saying $V_{N+1}^*(Q_{N+1}, T_o^N) \equiv 0$. This implies that the present worth at time $t = 0$ of value of energy from this anomaly after N years, is zero regardless of the value of Q_{N+1} and T_o^N . This effectively defines a horizon of "economic" relevance.

Let:

$R_N(Q_N + \Delta Q_N, T_o^N)$ = revenues in year N from pumping (and selling power) at rate $Q_N + \Delta Q_N$ and temperature T_o^N .

$I_N(\Delta Q_N, T_o^N)$ = capital investment in year N to increase pumping rate by ΔQ_N , assuming temperature during that period is T_o^N . Of course it is not likely that an optimal policy would include a capacity investment in the last year. Nevertheless, this option is available in this year, as in all the other $N-1$ years. This investment cost would also cover incremental power transmission costs.

$C_N(Q_N + \Delta Q_N, T_o^N)$ = operating cost during year N associated with producing at rate $Q_N + \Delta Q_N$ and temperature T_o^N .

$T_o^{N+1} = \phi(Q_N + \Delta Q_N, T_o^N)$, where $\phi(\cdot, \cdot)$ is a functional expression relating Q_N , ΔQ_N and T_o^N to T_o^{N+1} . This "transfer" function reflects the parameters of a non-steady-state hydrothermal model. Perhaps Professor Witherspoon's hydraulically steady state hydrothermal model could be used to estimate pertinent values of $\phi(\cdot, \cdot)$.

Then we have:

$$V_N^*(Q_N, T_o^N) = \max_{\Delta Q_N} \left\{ R_N(Q_N + \Delta Q_N, T_o^N) - I_N(\Delta Q_N, T_o^N) - C_N(Q_N + \Delta Q_N, T_o^N) + \alpha V_{N+1}^*(Q_N + \Delta Q_N, T_o^{N+1}) \right\},$$

$$\text{s.t. } T_o^{N+1} = \phi(Q_N + \Delta Q_N, T_o^N),$$

where:

$$a = 1/(1+i)$$

However, since $V_{N+1}^*(Q_{N+1}, T_o^{N+1}) \approx 0$,

$$V_N^*(Q_N, T_o^N) = \max_{\Delta Q_N} \left\{ R_N(Q_N + \Delta Q_N, T_o^N) - I_N(\Delta Q_N, T_o^N) - C_N(Q_N + \Delta Q_N, T_o^N) \right\}$$

Basically, this says the best value of the system in state (Q_N, T_o^N) at the beginning of period N , can be found by maximizing the expression in braces over all values of ΔQ_N . The value of ΔQ_N that maximizes will be ΔQ_N^* . Most likely ΔQ_N^* will be zero for this last period.

We find ΔQ_N^* for each pertinent value of Q_N, T_o^N , and then move back to the beginning of period $N-1$, writing:

$$V_{Q_{N-1}, T_o^{N-1}} = \max_{\Delta Q_{N-1}} \left\{ R_N(Q_{N-1} + \Delta Q_{N-1}, T_o^{N-1}) - I_{N-1}(\Delta Q_{N-1}, T_o^{N-1}) - C_{N-1}(Q_{N-1} + \Delta Q_{N-1}, T_o^{N-1}) + \alpha V_N^*(Q_{N-1} + \Delta Q_{N-1}, \phi(Q_{N-1} + \Delta Q_{N-1}, T_o^{N-1})) \right\} .$$

This is the typical two-stage optimization problem. Assuming $V_N^*(\cdot, \cdot)$ has some positive value, we trade-off value of energy extracted in period N with that removed in period $N-1$, as various values of ΔQ_{N-1} are considered. This is done for all pertinent values of Q_{N-1}, T_o^{N-1} and then we move back to period $N-2$ and repeat the two-stage optimization again. If energy extraction from this anomaly is at all economically feasible, at least one of the ΔQ_t will be positive.

This backward stepping recursive algorithm is then used iteratively until we compute $V_o^*(Q_o, T_o^o)$, where

$$Q_o = 0$$

$$T_o^o = \text{initial, equilibrium temperature of the aquifer.}$$

We can then move forward through this set of equations and find \bar{Q}^* , the optimal pumping policy vector.

Proposed Work

The next step in developing these economic models is to quantify the functions L, g, h and ϕ , and obtain solutions to the models outlined above. Perhaps the most important part of these results would be a sensitivity analysis indicating the relative importance of the above functions and such parameters as the discount rate.

A logical extension would be to investigate various geometries and spacing (in plan view) of production and recharge wells with these economic models. This extension would consider multiple well clusters for a single anomaly. A more comprehensive extension would include development of multiple, hydraulically-independent anomalies.

ECONOMIC MODELING FOR GEOTHERMAL RESERVOIRS AND POWERPLANTS

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Our work on reservoir modeling is mainly from a cost accounting standpoint. Our interest has been concerned with the economic aspects of reservoir exploration, development, and operation and the impact of these activities on the ultimate cost of geothermal energy. We have modeled the above ground aspects of delivering energy from geothermal wells, but we have treated the below ground flow as a "black box" which yields a fluid of specified characteristics at the wellhead. We hope to include a physical simulation model of geothermal reservoirs in our economic model sometime in the future. We have developed, under ERDA sponsorship, an economic model for geothermal cost analysis, called GEOCOST.

The GEOCOST computer program is a simulation model which calculates the cost of generating electricity from geothermal energy. GEOCOST will simulate the production of electricity from most types of geothermal resources. It is composed of two principal parts: a reservoir model which simulates the exploration, development, and operation of a geothermal reservoir, and a powerplant model which simulates the design, construction, and operation of the powerplant. Five different powerplant types can be simulated: flashed steam, binary fluid cycle, a hybrid combined flashed steam-binary fluid cycle, total flow, and geopressed reservoirs.

Sensitivity analysis can be performed, using the reservoir and powerplant models, to determine the relative effect of different economic parameters, assumptions, and uncertainties on the cost of generating electricity. The GEOCOST program can be used to:

- determine the economic incentives for specific geothermal research and development programs and projects.
- determine potential economic impacts of uncertainties in technology.
- identify major cost components of geothermal energy, and
- provide a systematic method for assessing the economic potential for each type of geothermal resource and power cycle.

Combined with resource assessment information, GEOCOST can be used to define the potential supply curve (price/quantity relationship) for geothermal energy. This supply curve forms the basis for: 1) assessing the potential role of geothermal energy in competition with other sources of energy, and 2) estimating potential economic incentives for new research and development programs.

GEOCOST can simulate nearly any financial and tax structure through varying the rates of return on equity and debt, the debt-equity ratios, and tax rates. The reservoir model and the powerplant model may have the same or separate financial structures and costs of capital. The plant and reservoir life can be varied over a long period, currently up to 50 years.

The **GEOCOST** program calculates the cost of energy based on the principle that the present worth of the revenues will be equal to the present worth of the expenses including investment return over the economic life of the plant and/or reservoir. The present worth factor is determined by the capital structure and rates of return on invested capital for the enterprise.

The results of analyses using the **GEOCOST** model have shown that the reservoir characteristics, in particular the fluid temperature, well flow rate, and well drilling and fluid extraction costs, are the most important variables which will determine the cost of geothermal energy.

PHYSICAL MODELS OF STIMULATED GEOTHERMAL RESERVOIRS

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As part of the geothermal energy program at Stanford University, physical models have been developed to evaluate optimum performance of fracture-stimulated geothermal reservoirs. Three such efforts reported in this summary are: laboratory simulation of an explosion-produced rubble chimney to obtain experimental data on the extractability of heat from hot rock by in-place boiling; heat and mass transfer transients with individual porous rock fragments to compare their relative importance in stimulated systems; and measurement of radon emanation from geothermal reservoirs as a tracer for reservoir engineering studies. Definitive progress has been achieved with each of these physical models.

Hunsbedt, Kruger, and London (1975a) reported the progress on the construction and operation of a 19-ft.³ laboratory model of an explosion-produced rubble chimney (shown in the production mode in Fig. 1.b) to study the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs. It had been noted by Ramey, Kruger, and Raghavan (1973) that although considerable energy is available from hydrothermal resources, most of this energy is stored in the aquifer host rock. Production by some nonisothermal process, such as in-place boiling or colder fluid recirculation, might be valuable for increasing heat extraction from natural or stimulated hydrothermal or hot rock geothermal resources.

Recent results by Hunsbedt, Kruger, and London (1975b) show that heat extraction obtained by pressure reduction which allows boiling to occur in the rubble chimney resulted in rock energy extraction fractions in excess of 0.75 under various experimental conditions. The degree of rock energy extracted depended on such parameters as height of liquid level, extent of condensed steam reflux, rate and temperature of cooler-water recharge, and rock to steam temperature difference which in turn depends on rock particle size and cooldown rate. In this high-permeability fractured rock system, recovery of available thermal energy ranged from 1.25 to 2.58 times the energy extractable by flashing the initial in-place fluid alone. Parameters noted to affect the extent of heat recovery included the external heat transfer parameter, rock porosity, initial reservoir conditions and enthalpy of the recharge fluid. Predictive models were developed for the laboratory model system based on mass-energy balance for comparison with the experimental data. Agreement was satisfactory for these experiments, other than recharge with cool water which produced non-uniformity in the axial temperature distribution. Evaluation of the results from the laboratory model are underway to scale the parameters to real-size stimulated reservoirs.

A second physical model was developed to examine microscale processes of mass and heat transfer in fracture stimulated reservoirs, based on two types of void space: macropores, defined as void volume between rock

fragments; and micropores, defined as pore space inside individual rock fragments. The importance of mass transfer between hot geofluid in micropores and colder circulating fluids in macropores on heat extraction rates from fractured geothermal reservoirs was investigated. In the physical model, both mass transfer, using HTO as a tracer for the micropore water, and heat transfer, using a sensitive quartz thermometer, from artificial porous spheres were measured under similar experimental conditions.

Kuo, Brigham, and Kruger (1975) compared the molecular diffusivity associated with mass transfer as a function of porosity with the thermal diffusivity associated with heat transfer as a function of mixing rate. They noted that the ratio of the effective molecular diffusion and thermal diffusion coefficients was about 3×10^{-4} , indicating that even for very porous fragments heat transfer is a much more rapid process than mass transfer. Analytical models for the heat and mass transfer transients for spherical rocks agree with these indications, but suggest that a film coefficient in the model is desirable. Efforts are underway to investigate heat transfer transients for irregular shaped rocks.

Radon has been shown by Stoker and Kruger (1975) and Kruger and Umara (1975) to have potential as an internal tracer for reservoir engineering studies because of a unique combination of nuclear, chemical, and physical properties, its emanating power in geothermal reservoirs, and its transport characteristics in hydrothermal fluids. Interest in radon in geothermal reservoirs developed as a potential means to evaluate the creation of new surface area by reservoir stimulation techniques, such as hydraulic, thermal-stress, and explosive fracturing, and concern about the environmental release of radon and its short-lived radioactive products. However, since stimulated reservoirs are not available for testing, studies were concentrated on the emanation properties of radon in existing production geothermal wells as a function of steady-state and transient flow rate.

Radon concentration in geothermal fluids is noted to vary not only by resource type but also within individual wells in a given geothermal field. Temporal variations at steady flow rate are within useful limits. Models have been initiated to examine the dependence of radon concentration on flow rate, with a vertically linear model for vapor dominated systems and a horizontal radial model for liquid dominated systems. An initial test at the Geysers steam field, shown in Figure 2, indicates a transient reduction in radon concentration to about half value over the three-week period following an instantaneous reduction in flow rate to half value. An excursion in radon concentration was noted during the onset of a period of seismic activity in the region. Additional tests at this field and similar tests at other steam fields and some hot water fields are being planned to evaluate the relationship of radon concentration under reservoir transient conditions.

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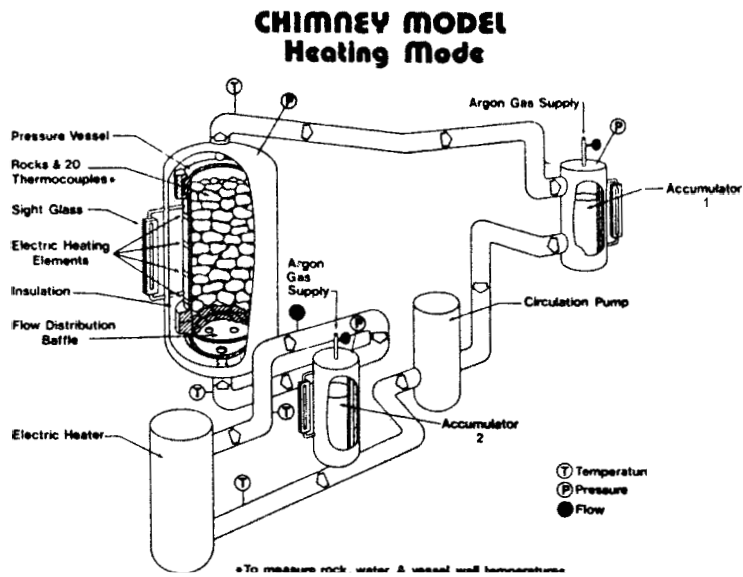


Figure 1.a Diagram of Chimney Model System - Heating Mode Operation

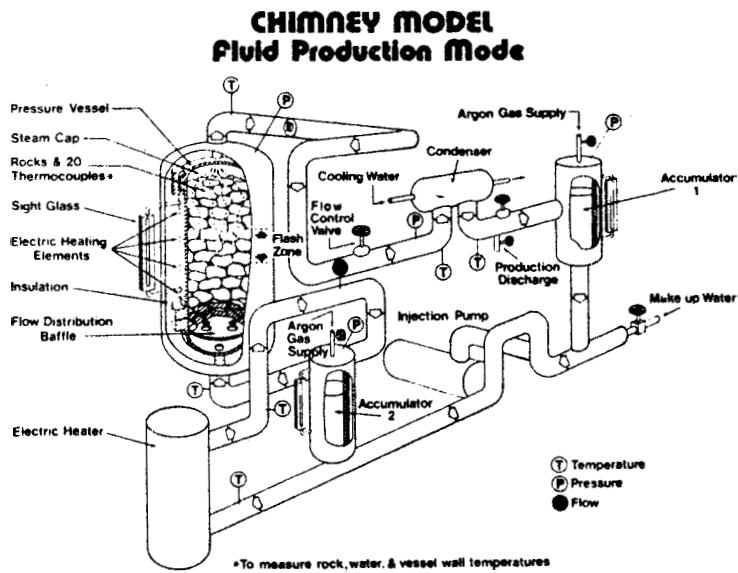


Figure 1.b Diagram of Chimney Model System - Fluid Production Mode Operation

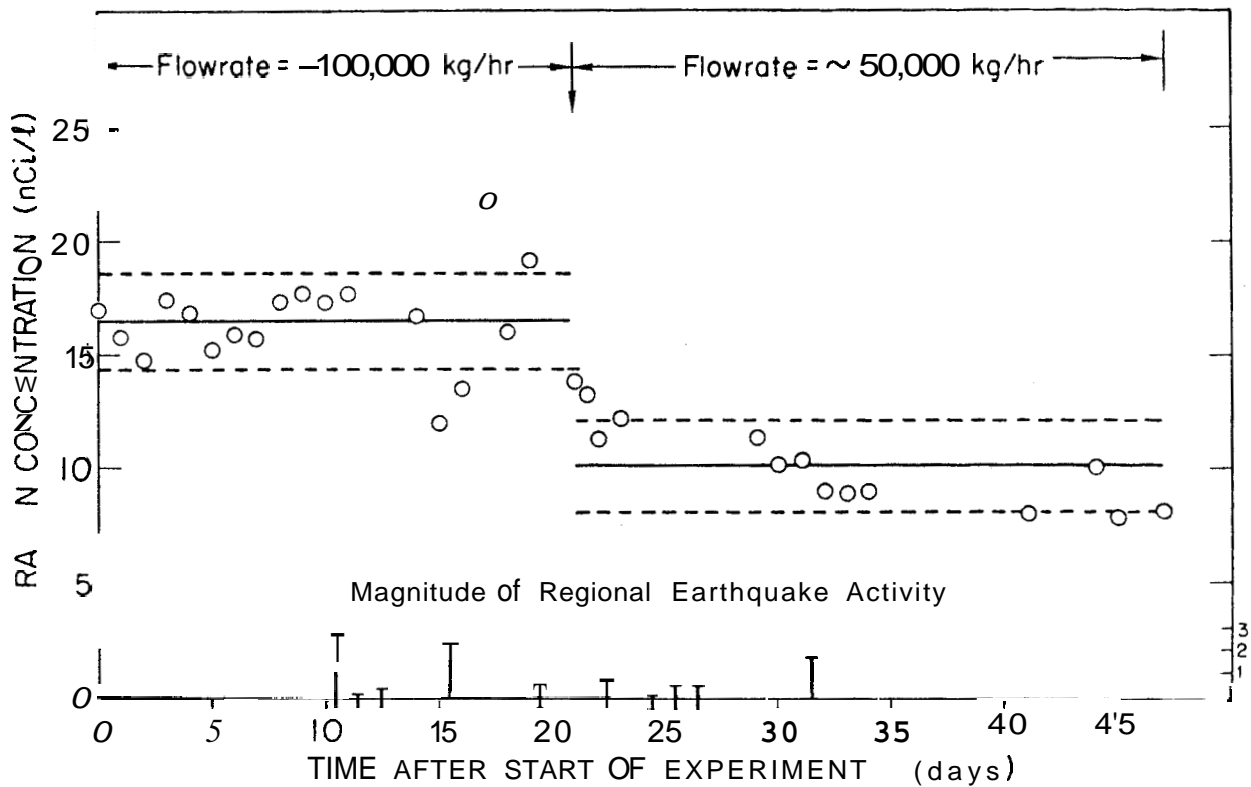


Figure 2 Radon concentration as a function of flow rate. Solid lines are the mean values over the flow rate period. Broken lines represent one standard deviation. Also shown is the magnitude of regional earthquake activity on the Richter scale.

HYDRAULIC-FRACTURE GEOTHERMAL RESERVOIR ENGINEERING

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The Dry Hot Rock Geothermal Energy Program being conducted by the Los Alamos Scientific Laboratory has been described in detail by Smith et al.¹ Basically we have proposed that man-made geothermal energy reservoirs can be created by drilling into relatively impermeable rock to a depth where the temperature is high enough to be useful; creating a large hydraulic fracture; and then completing the circulation loop by drilling a second hole to intercept the hydraulic fracture.

Thermal power is extracted from this system by injecting cold water down the first hole, forcing the water to sweep by the freshly exposed hot rock surface in the reservoir/fracture system, and then returning the hot water to the surface where the energy is removed from the water by the appropriate power producing equipment. System pressures are maintained such that only one phase, liquid water, is present in the reservoir and the drilled holes.

In the discussion to follow, the beneficial effects of thermal stress cracking, anticipated because of the cooling and thermal contraction of the rock, will be ignored. Instead, it will be assumed that the fluid flow is entirely confined to the gap between the impermeable rock surfaces and that heat is transferred to this fluid only by means of thermal conduction through the solid rock.

RESERVOIR FEATURES AND EXPECTED PERFORMANCE

Based upon the theory of elasticity and brittle material fracture mechanics², we idealize the fracture as being circular with a fracture gap width, w , which varies elliptically with radius. The maximum fracture width is extremely small compared to the maximum fracture radius, R ; a typical value being 3 mm (1/8 in.) for a radius of 500 m (1640 ft). Furthermore, since the direction of the least principal earth stress is expected to be horizontal, we anticipate that the fracture plane will be vertically oriented, indicating that fluid buoyancy effects may be important.

The maximum thermal power that can be extracted from the rock surface occurs when the entire rock surface is suddenly and uniformly lowered in temperature from its initial value, T_r , to the cold water injection temperature, T_i . This power, E , is given as a function of time, t , by³

$$E = 2\pi R^2 \sqrt{\frac{\lambda \rho_s c_s}{\pi t}} (T_r - T_i) ,$$

where λ , ρ_s , and c_s are the thermal conductivity, density, and specific heat capacity of the rock. Because the thermal conductivity of the rock is small, it can be shown that rather large fracture radii are required to produce significant amounts of power for reasonable periods of time. For example, if the temperature difference, $T_r - T_i$, is 200°K , a 500 m fracture is required if one wishes to be able to produce at least 25 MW(t) continuously for 10 years. To continue this same example, it can be shown³ that even after 10 years the initial rock temperature is diminished less than 5% for distances of 40 m or more away from the fracture surface. Thus, it is seen that heat is being removed from the rock only in a relatively narrow zone immediately adjacent to the fracture, and we conclude that even for more complicated examples, where the surface temperature is not uniform, the conduction in the rock will be essentially one dimensional; perpendicular to the plane of the crack.

A simple heat balance shows that the minimum water flow rate, Q , required to produce the power is given by

$$Q = \frac{E}{\rho c (T_r - T_i)} \quad ,$$

where ρ and c are the density and specific heat capacity of water. Using typical values it can be shown that our 25 MW(t) example will require a minimum flow rate of $0.03 \text{ m}^3/\text{sec}$ ($1 \text{ ft}^3/\text{sec}$ or 500 gpm). Since this flow is confined within the very narrow fracture, the water velocities will be of the order of 0.02 m/sec (0.07 ft/sec); quite high compared to, say, the usual flow velocities through porous media, and we conclude that heat transport due to fluid conduction is negligible compared to fluid convection.

RESERVOIR SIMULATION MODELS

Fluid flow and fluid heat transport are idealized as being two dimensional, in the plane of the fracture. The horizontal coordinate is taken as x , the vertical coordinate as y . Solid rock conduction takes place along the z -coordinate, perpendicular to the x - y plane. Using Darcy's law with a permeability for an open fracture of $\frac{w^2}{12}$, the x and y direction velocities become

$$u = - \frac{w^2}{12\mu} \frac{\partial P}{\partial x} \quad (1)$$

$$v = - \frac{w^2}{12\mu} \left[\frac{\partial P}{\partial y} - \rho g \beta (T - T_o) \right] \quad (2)$$

where the extra term in the equation for v represents the effects of buoyancy. Making the Boussinesq approximation the equations of conservation of mass and energy in the flowing water are

$$\left(\frac{w^3}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial P}{\partial y} - g(T - T_o) \right) \quad (3)$$

$$\rho c_w u \frac{\partial T}{\partial x} + \rho c_w v \frac{\partial T}{\partial y} - 2e = 0 \quad (4)$$

Finally the rock conduction equation is

$$\frac{\partial \theta}{\partial t} = \frac{\lambda}{\rho_s c_s} \frac{\partial^2 \theta}{\partial z^2} \quad (5)$$

subject to the initial and boundary conditions

$$\theta(x, y, z, t=0) = T_r \quad (6)$$

$$\theta(x, y, z=0, t) = T(x, y, t) \quad (7)$$

$$\theta(x, y, z \rightarrow \infty, t) = T_r \quad (8)$$

The additional nomenclature is as follows:

w = fracture width

P = pressure

μ = viscosity

ρ = reference water density (evaluated at T_o)

T_o = reference temperature

T = temperature of the fluid

g = acceleration of gravity

β = volumetric expansion coefficient of water

θ = temperature of the rock

e = the flux of energy delivered to the water by one rock surface; evaluated as $e(t) = \lambda \frac{\partial \theta}{\partial z}(x, y, z=0, t)$.

Equations (3) through (8) represent a considerable simplification of the equations first proposed in the pioneering work of Harlow and Pracht⁴ and continued by McFarland.⁵ These writers had at their disposal very

powerful numerical methodologies^{6,7} which made it convenient to include advection as well as transient terms in Eq. (3), and conduction and transient terms in Eq. (4). By formal nondimensionalization and rationalization of the complete equations it can be shown⁸ that these additional terms are negligible for calculations of practical interest.

At present the solution procedure consists of first solving the rock conduction Eq. (5), with Eqs. (6) through (8), via Duhamel's superposition integral,⁹ and then differentiating the result to evaluate e. Thus

$$e(x, y, t) = \lambda \frac{\partial \theta}{\partial z}(x, y, 0, t) = \int_0^{\tau=t} \sqrt{\frac{\lambda \rho_s c_s}{\pi(t-\tau)}} \frac{\partial [T_r - T(x, y, t)]}{\partial t} d\tau. \quad (9)$$

This solution for e is substituted into Eq. (4). One then has a set of two coupled, nonlinear, time varying, integro-differential equations for T and P. This set of equations is then solved numerically via finite difference analogues to the real equations.⁸

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MODEL EXPERIMENTS IN HYDRAULIC FRACTURE

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Hydraulic fracturing of rock cannot be seen in situ, and the end result must mostly be judged on basis of roundabout evidence. As there is no question about the desirability of visual observations and direct measurements, the only way out of the dilemma seems to lie in experimental models. This part of the work carried out at Northwestern University is therefore directed toward the development of suitable experimental techniques and transparent laboratory models that could be used to simulate the various problems associated with drilling into hard impermeable rock and fracturing it for energy extraction.

The material selected for the transparent models is epoxy resin (Epon 828 resin with phthalic anhydride hardener). This material is commonly used for three-dimensional photoelastic experiments which employ the stress freezing technique. The principal reason for using this material, at least for the present, in studies of hydraulic fracture is that it can be cast into large blocks with relative ease in the laboratory. The only equipment needed for this purpose is a curing oven with accurate temperature control.

The model consists of a block of the transparent epoxy resin. A hole is drilled into the block, and stainless steel tubing is cemented into the hole. The tube terminates at about two diameters from the bottom of the hole. The stainless steel tubing used is 0.063 in. OD, 0.018 in. wall and is capable of withstanding pressures up to 36000 psi. The hole is drilled and reamed so that there is about 0.002 in. radial clearance between the block material and the tube. The drilling of accurate holes in the epoxy resin is a tedious operation because of the large length, say 4 in., in comparison to the diameter.

A special technique had to be developed for cementing the stainless steel tubing into the model block. First a pool of the cement is placed on the surface of the block around the tube. Then a fixture in the form of a cup is attached to the surface of the block. The fixture seals against surface of the block, but connects the end of the tube to the atmosphere. Next the space between the surface of the block and the cup-like fixture is pressurized to about 40 psi. This drives the cement from the pool into the clearance between the hole and the tube. The flow is rather slow because of the high viscosity of the cement and the small clearance, and it can be observed visually from the change in contrast. Finally, the pressure is removed before the cement has a chance to flow into the tube and plug it.

In case the initial orientation of the hydraulic fracture must be controlled, as in experiments intended to study the interaction between two hydraulic fractures, a small penny-shape crack is introduced at the

bottom of the hole before cementing the tubing into the hole, The best means of prefracturing was found to be pressing a rod that fits into the hole and is sharpened to a wedge against the bottom of the hole.

The fluid used in the fracture experiments is mercury. There are two reasons for choosing mercury: First, its high bulk modulus minimizes the energy stored behind the fracture as it is initiated, and thus avoids catastrophic growth in the initial stages. Second, the fractures filled with mercury are perfectly visible.

Several experiments have been done on the interaction and joining of two hydraulically induced fractures. The observed interaction and the subsequent behavior of such cracks after joining is quite fascinating. For instance, the interaction was seen to be very strong for cracks in parallel planes. Such cracks were observed to have the tendency to join and curve sharply toward each other. The growth after joining led to very intricate three-dimensional shapes. It was also seen that, **if** one crack is kept at constant volume and the second made to expand, the shape of the first crack changes as the second fracture approaches it. In fact, it was observed that under these circumstances the first fracture may even close over part of its extent.

ANALYTICAL STUDY OF CRACK GROWTH AND SHAPE BY
HYDRAULIC FRACTURING OF ROCKS

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Crack shape, orientation, size and growth due to hydraulic fracturing will be investigated as a problem in three dimensional elasticity theory. Since the opening of the crack by hydraulic fracture, the pressurizing of the treatment fluid, the leaking off of the fluid, and the thermal cracking are simultaneous events, the theory of elasticity will be coupled with fluid mechanics and the theory of heat conduction. The results, which include the coupling of elasticity and fluid inclusion, will be obtained by analytical techniques so that they can be presented with analytical formulae when possible.

Stress intensity factors for an elliptic crack. By using the continuous dislocation method developed by Mura (1963) and Willis (1968), the stress component σ_{33} , which is the most important component, along an elliptical crack (Figure 1) under a linearly changing applied stress $\sigma_{33}^0 = A + Bx_1 + Cx_2$ has been obtained as follows:

$$\sigma_{33} = \frac{a_2 \left(\frac{x_1^2}{a_1^2} + \frac{x_2^2}{a_2^2} \right)^{\frac{1}{2}}}{\left(\frac{x_1^2}{a_1^2} + \frac{x_2^2}{a_2^2} - 1 \right)^{\frac{1}{2}}} \left(\frac{A}{E} + \frac{Bx_1}{3E_1} + \frac{Cx_2}{3E_2} \right) \quad (1)$$

where

$$E = \int_0^{\pi/2} (1 - k^2 \sin^2 \varphi)^{\frac{1}{2}} d\varphi$$

$$k^2 = \left(a_1^2 - a_2^2 \right) / a_1^2 > 0$$

$$E_1 = \int_0^{\pi/2} \sin^2 \varphi (1 - k^2 \sin^2 \varphi)^{\frac{1}{2}} d\varphi$$

$$E_2 = \int_0^{\pi/2} \cos^2 \varphi (1 - k^2 \sin^2 \varphi)^{\frac{1}{2}} d\varphi \quad (2)$$

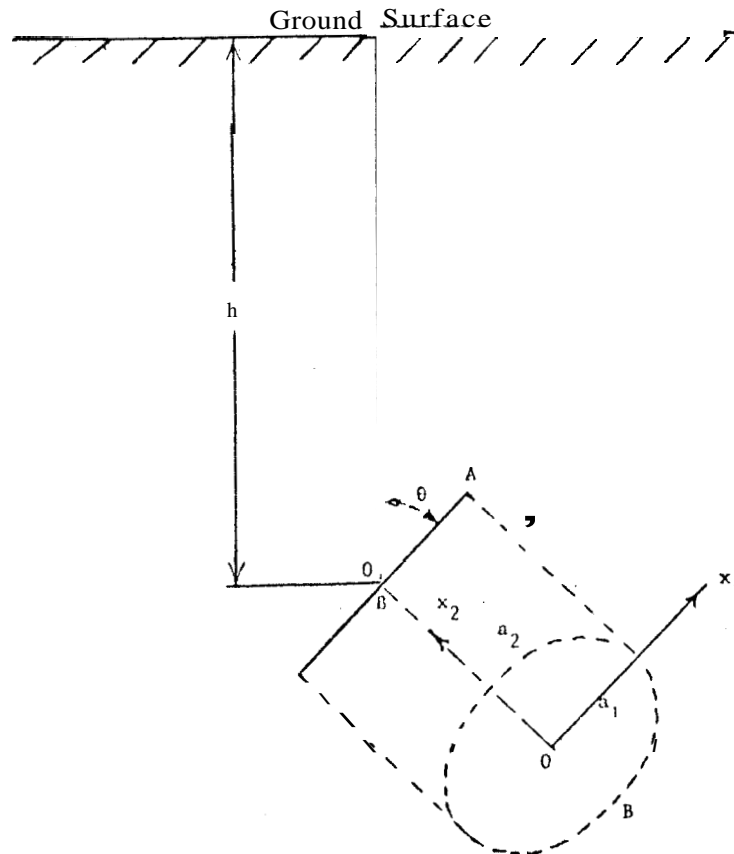
On the crack surface the boundary condition

$$\sigma_{33} + \sigma_{33}^0 = 0$$

is satisfied. For the crack as shown in Fig. 1

$$\sigma_{33}^0 = \rho_0 g(h - x_1 \cos\theta) + p - S \quad (3)$$

and therefore, $A = -\rho_0 gh + p - S$, $B = \rho_0 g \cos\theta$, $C = 0$, where p is the pressure necessary for crack opening, ρ_0 the density of the rock, h , the depth of the crack, S , tectonic stresses and θ is the orientation of the crack surface relative to the surface of the earth (Fig. 1).



Fig, 1

The maximum width of the crack also has been obtained as

$$w = \left(1 - \frac{x_1^2}{a_1^2} - \frac{x_2^2}{a_2^2}\right)^{\frac{1}{2}} \frac{A a_2}{\mu E} 2(1 - \nu) \quad (4)$$

where ν is Poisson's ratio, μ is the shear modulus, and E is defined in Eq. (2).

The stress intensity factor is the coefficient of $(\frac{x_1^2}{a_1^2} + \frac{x_2^2}{a_2^2} - 1)^{\frac{1}{2}}$ in Eq. (1). The stress intensity factor is not constant along the crack

edge. However, certain angles θ of crack inclination give equal stress intensity factor at the crack tips of the major and minor principal axes of the crack. Thus, θ can be obtained as

$$\theta = \cos^{-1} \left[\frac{3E_1}{E} \frac{A}{a_2 \rho_0 g} (1 - a_2/a_1) \right] \quad (5)$$

Axisymmetrical crack growth in hydraulic fracturing. It is found that the growth rate of a penny-shaped crack can be predicted as a continuous function of time, when the crack is fractured by water under hydraulic pressure.

The fundamental equations are

$$\frac{\partial(\rho w)}{\partial t} + \frac{1}{r} \frac{\partial(rq)}{\partial r} = 0 \quad (6)$$

$$\frac{\partial p}{\partial r} = - \frac{12\mu}{\rho w^2} q - \frac{6}{5wr} \frac{\partial}{\partial r} (rq^2/\rho w) - \frac{1}{w} \frac{\partial q}{\partial t}$$

where p is the fluid pressure in the crack and q is the rate of mass flow defined by

$$q = \rho w \bar{u} \quad (7)$$

where \bar{u} is the average radial fluid velocity. According to Sneddon and Elliott (1946), we have for the width of the crack and the stress intensity factor:

$$w = \frac{8(1 - \nu^2)}{\pi E} \int_r^R \frac{r_1 dr_1}{\sqrt{r_1^2 - r^2}} \int_0^1 \frac{x(p - S)}{\sqrt{1 - x^2}} dx \quad (8)$$

$$K = \frac{1}{\pi} \sqrt{\frac{2}{R}} \int_{R_0}^R \frac{r(p - S)}{\sqrt{R^2 - r^2}} dr \quad (9)$$

where R is the crack radius, R_0 is the wellbore radius, and E is Young's modulus for the crack; S is the tectonic stress.

Since $w = 0$ at $r = R$ and (6) has the inverse cube singularity for w , we assume that the second equation in (6) holds for the domain, $R_0 \leq r \leq R_1$, where $R_1 < R$ and indicates the radius of the wetted domain. It follows that

$$\bar{u}(R_1) = \frac{dR_1}{dt} \quad (10)$$

Investigation of order of magnitude of the terms in (6) leads to the conclusion that the last two terms in the right-hand side can be neglected. The following global equation of the conservation of mass is also employed

$$\int_{R_o}^{R_1} \rho r w dr = \int_0^t q_o R_o dt \quad (11)$$

where q_o is the flow rate at the wellbore.

Results obtained by solving (6) to (9) and (11) are given in Figs. 2 and 3, where

$$t_D = 3\pi E q_o t / 8(1 - \nu^2) \rho S R_o^2, \quad w_D = \pi E w(R_o) / 8(1 - \nu^2) R_o S, \quad \Delta p_D = (\bar{p} - S) / S$$

and \bar{p} is the average pressure. The solutions by neglecting the effect of the elliptic integral in w which arises from (8) and the effect of the term $\partial(\rho w) / \partial t$ in (6) are shown in Fig. 2 by putting subscripts (1) and (2), respectively. It is found that the former effect is small for large values of R/R_o while the latter one is significant. Results, which are valid for a wide range of R/R_o , are shown in Fig. 3. The effect of the stress intensity factor of the rock is found to be significant even for large values of R/R_o .

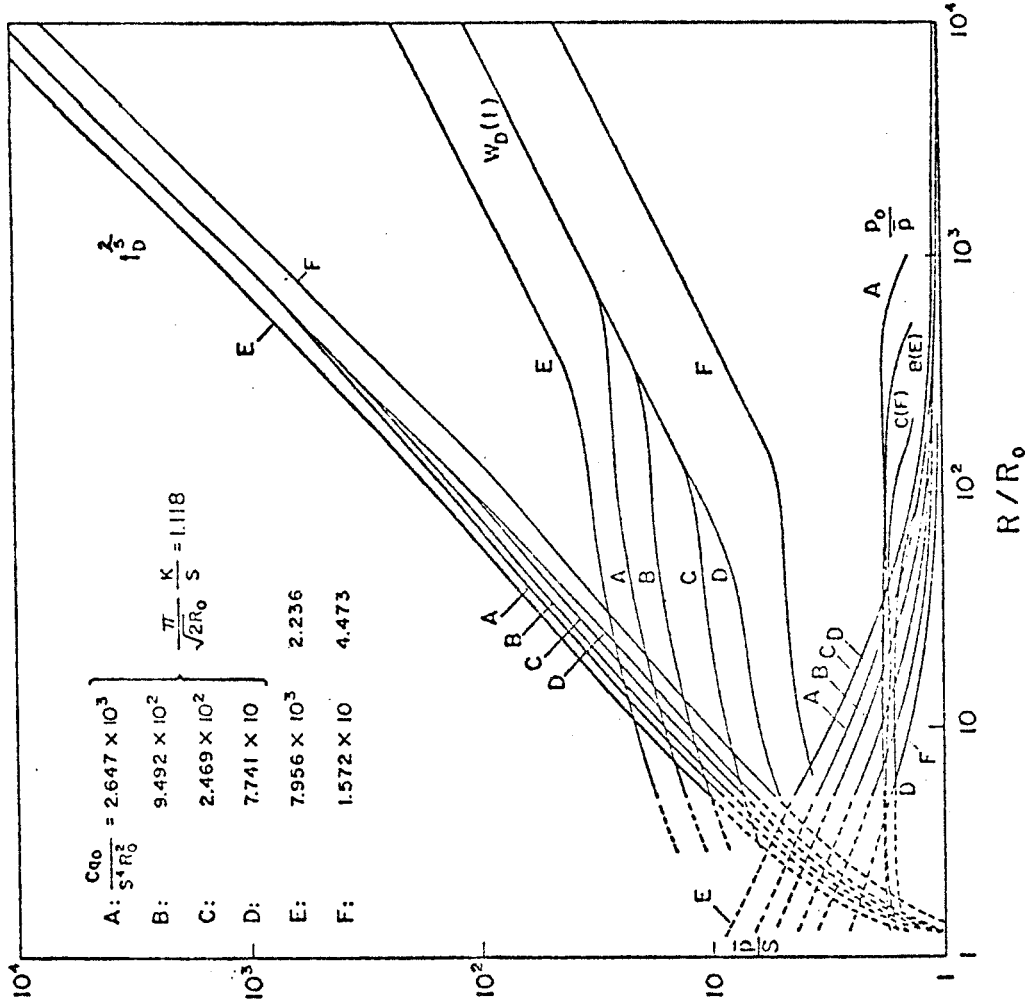


Fig. 3. Expansion of crack by action of fluid flow with constant flow rate; relative nondimensional width $w_D(t)$, nondimensional time t_D , pressure ratios p_0/\bar{p} and \bar{p}/S with nondimensional fracture radius R/R_0 .

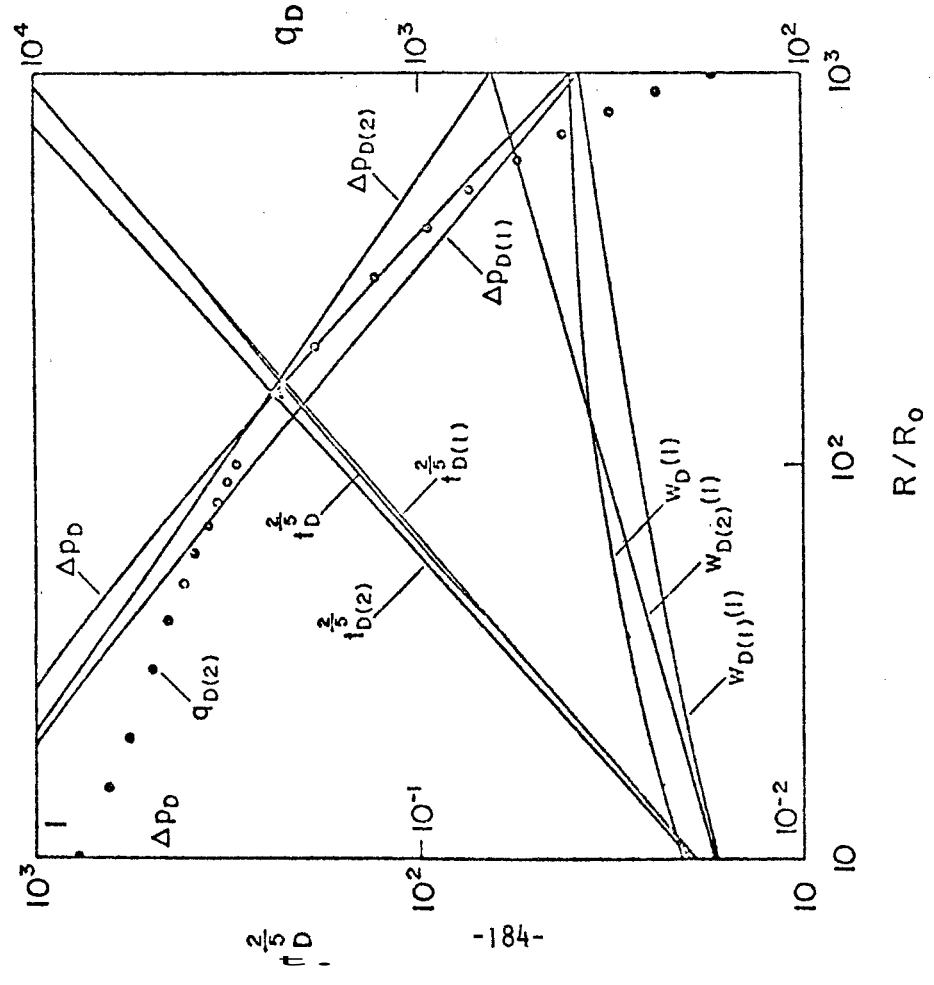


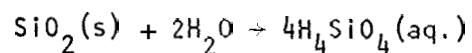
Fig. 2. Effects of terms in the basic equations on crack growth under constant flow rate
 $q_D = Cq_0/S^4 R_0^2 = 7.6961 \times 10^3$
 $C = 3\pi E u / 128(1 - \nu^2)^3$.

CONTROL OF SILICA SCALING

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Both the equilibrium chemistry of silica solubility and kinetics of the dominant reactions suggest methods of preventing scale formation in the development of hot water-dominated geothermal resources.

At equilibrium, the dominant solubility-fixing reaction is



for pH's less than 9, - the usual condition. Starting with a geothermal solution of a specific silica concentration, precipitation may be initiated by decreasing temperature (Fig. 1) or water purity (Fig. 2). The stoichiometry of this reaction shows that the solubility is a function of

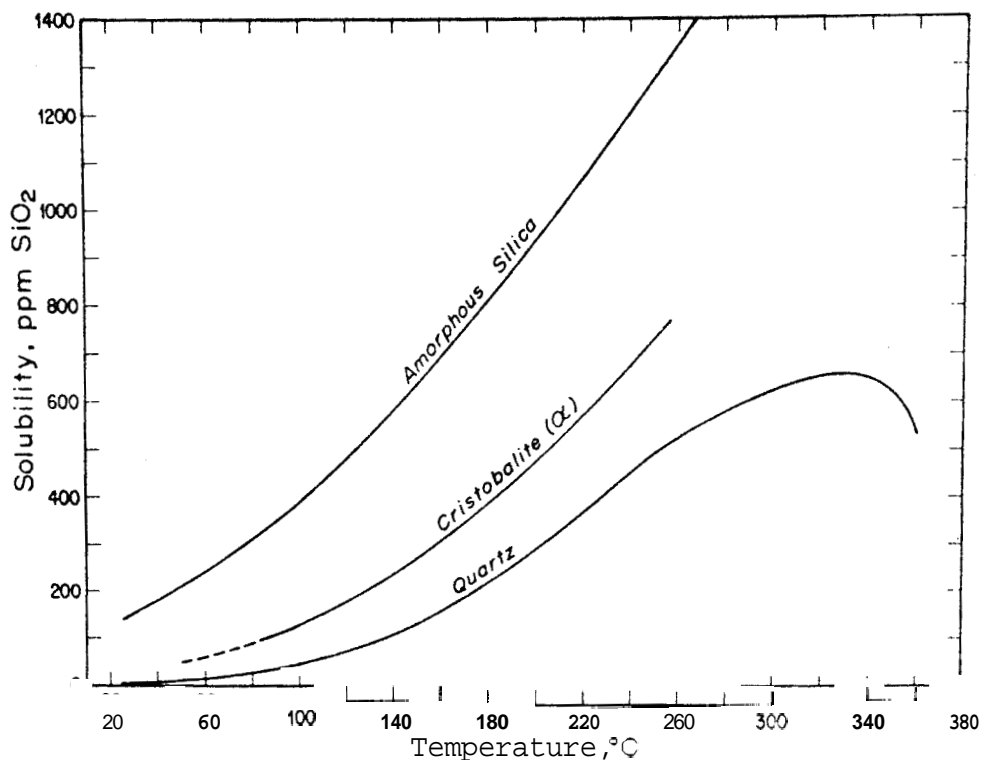


Fig. 1. Solubility of silica phases in water. (Data from references 1, 2, 3, 4, 5, 6, 8, 9, and 11.)

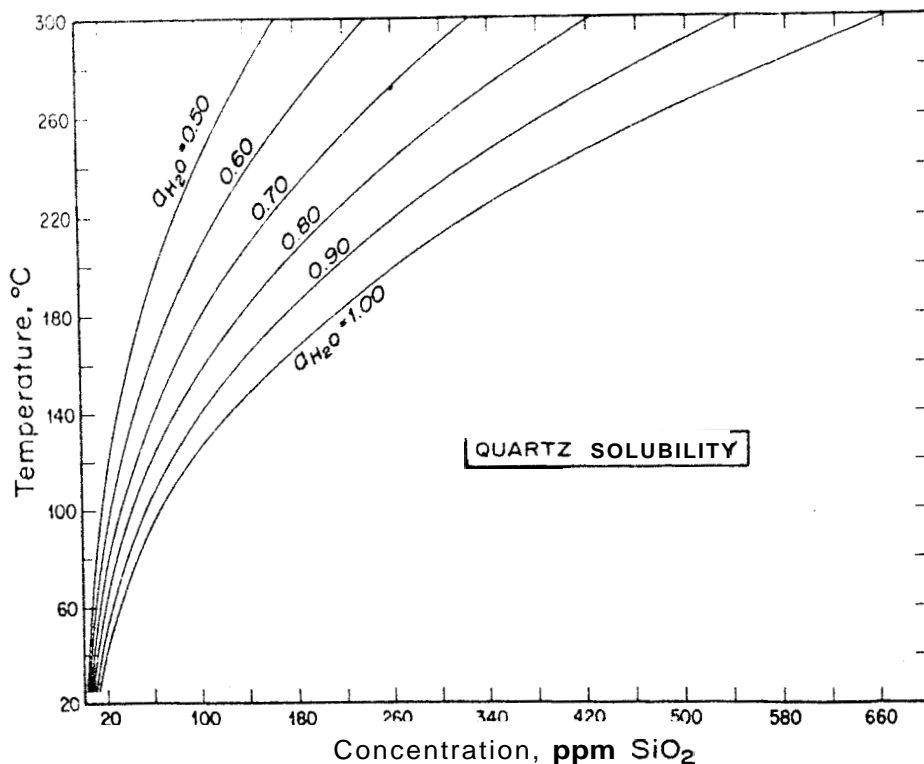


Fig. 2. Quartz solubility at various temperatures and activities of water. The activity of water varies with salt concentrations typically as follows:

a_{H_2O}	Concentrations		CaCl ₂	
	NaCl			
— 2.0	m	%	m	%
0.90	2.8	14	1.6	15
0.75	6.2	27 (sat. at 25°C)	-	-
0.70	-	-	3.4	22
0.50	-	-	5.0	36
0.30	-	(sat. at 25°C)	7.2	44

These values are exact for temperatures near 25°C and approximately correct to 350°C.

water activity, $a_{H_2O}^2$, as demonstrated by the linearity of the curve on Fig. 3, so that an increase in ionic strength, due to evaporation (flashing) or to dissolving of salts, greatly reduces solubility. Consequently, equilibrium relations show that precipitation can be delayed by: (1) maintaining the temperature of the solution close to that of the geothermal reservoir for as long as possible prior to heat extraction, and (2) by dilution. In appropriate circumstances, favorable dilution can be

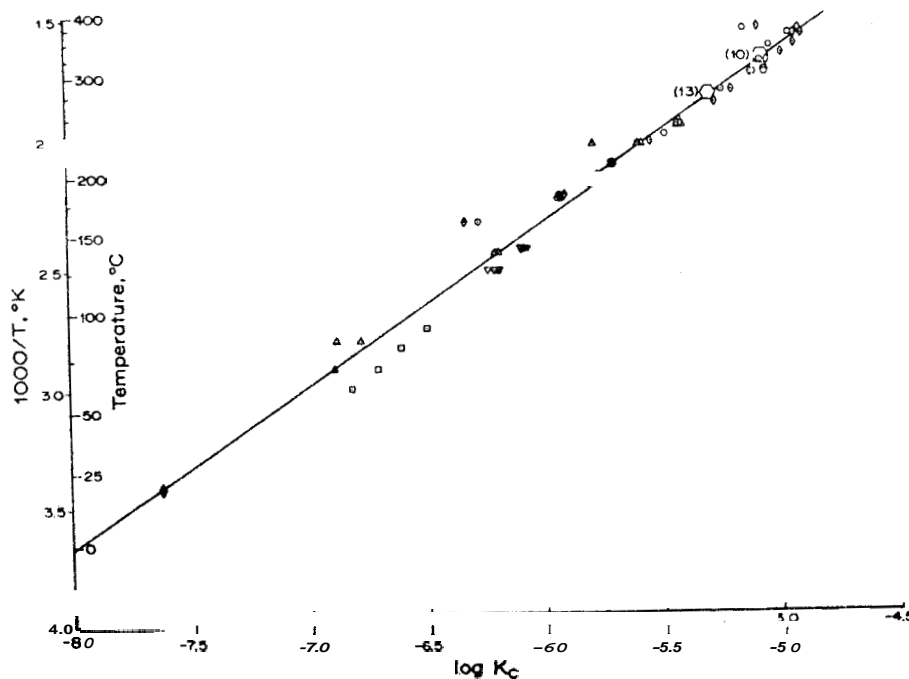


Fig. 3. The complete equilibrium constant for quartz

$$\text{solubility where } K_c = \frac{a_{H_4SiO_4}}{a_{SiO_2} (H_2O, g/cc)^2} .$$

(Solubility data from references 1, 4, 5, 6, 8, 9, and 11.)

realized by mixing the output from one well with that from a second with either lower salinity or silica content. Another process causing dilution is to use a steam-driven, downhole pump. Because flashed steam is always relatively pure compared to the residual solution, if this steam is injected to power the pump, the effluent also effectively dilutes both the initial silica content and the salinity, a dual bonus.

Kinetic effects are at least equally promising for controlling silica deposition. The rate of precipitation at temperature, T , is

$$\left(\frac{\partial (SiO_2)}{\partial t} \right)_T = K_p (H_4SiO_4) (S/V)$$

where K_p is the rate constant and (S/V) is the surface area on which deposition is taking place per unit volume of solution¹⁰. Clearly, the surface area (and roughness) in geothermal systems should be minimized to slow rates of deposition. Alternatively where supersaturation is inevitable, silica can be scrubbed from the solution by countercurrent

flow of fine-grained, inert solids (with high surface area) to nucleate and remove the excess silica.

Because K_p is exponentially dependent on temperature, the solution should not be allowed to cool slowly from high temperatures (Fig. 4). If saturation is reached at high temperatures, precipitation is fast due to the high rate of reaction. However, if the solution is cooled abruptly, the silica is quenched into solution and can only precipitate very slowly at low temperature. Consequently, single-stage heat extraction minimizes scale formation. Sufficient rate data have not as yet been accumulated to quantify this method, unfortunately.

Silica polymerization seems not to be important to the kinetics of geothermal systems. Rates are probably significant only at high alkalinities at high temperatures and at pH 8-10 at low temperatures. Furthermore, analyses of geothermal fluids by the monomer-detecting molybdate technique also appears to give reliable values for the total silica concentration present.

The severity of scale formation apparently also depends in part on salinity. Highly saline solutions, such as those from the Salton Sea KGRA, readily deposit massive scale while less saline solutions, as at Cerro Prieto, may not precipitate more than minor amounts before reaction.

	T °C	(Cl ⁻)		(SiO ₂)
		m	ppm	ppm
Salton Sea	320	3.1	155,000	400
Cerro Prieto	350	0.2	10,000	500

As suggested by several authors, this effect may be caused by catalysis of precipitation reactions by chloride concentrations above roughly 0.01 m¹⁰. At higher Cl⁻ concentrations, there is also the untested possibility that silica-chloride complexes form. Dilution of such brines is especially effective in retarding scale deposition. In addition to lowering the initial silica concentration and raising the ultimate solubility by increasing a_{H_2O} , the rate of deposition is lowered by decreasing the concentration of this catalyst. Again, considerable data are needed to determine the exact concentration ranges where catalysis and complexing become important. These values are being obtained as functions of time, temperature, and chloride concentrations using the experimental system shown on Fig. 5.

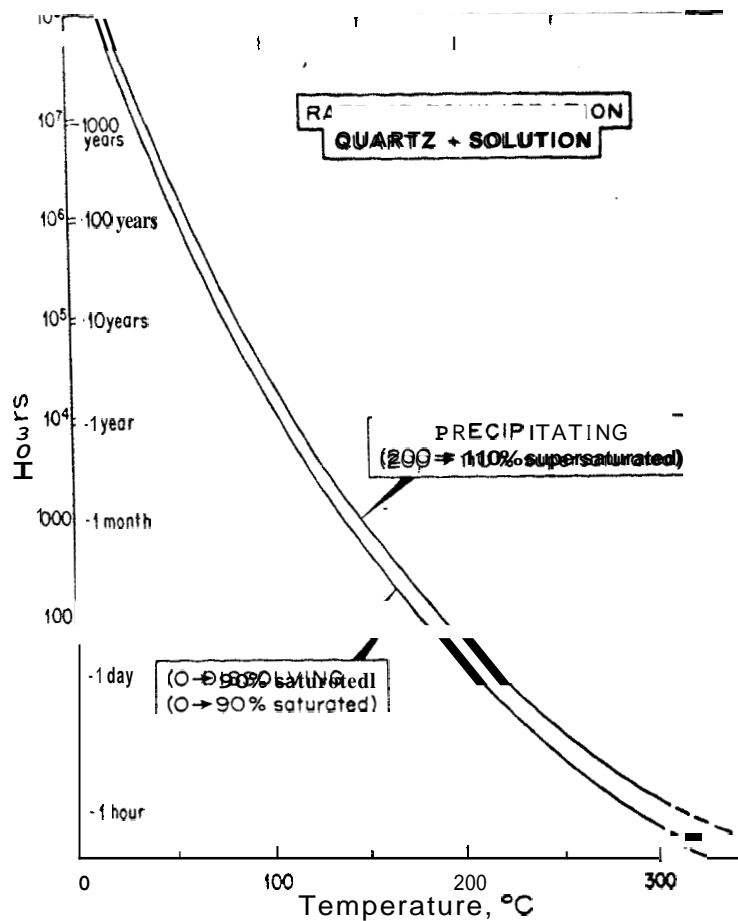


Fig. 4. Preliminary curves showing the rates of dissolving and precipitating of quartz as a function of temperature. Dissolving - Amount of time necessary for water in a geothermal reservoir to become 90% saturated with H_4SiO_4 if the ratio of the silica surface area to the volume of solution is $14.9 \text{ cm}^2/\text{ml}$ (equivalent in the reservoir to 1 ml of solution within a fracture of 1 in² area). Precipitating - Amount of time necessary for water in a pipe which contains twice the saturation concentration of H_4SiO_4 to precipitate enough quartz to reach 110% of saturation if the pipe has a ratio of surface area to volume of solution of $6.6 \text{ cm}^2/\text{ml}$ ($\sim 800 \text{ ft}^2/\text{gal}$).

These rates will be faster for cristobalite and amorphous silica in direct proportion to their higher a_{SiO_2} and also higher due to any catalysis, for example by F^- or Cl^- .

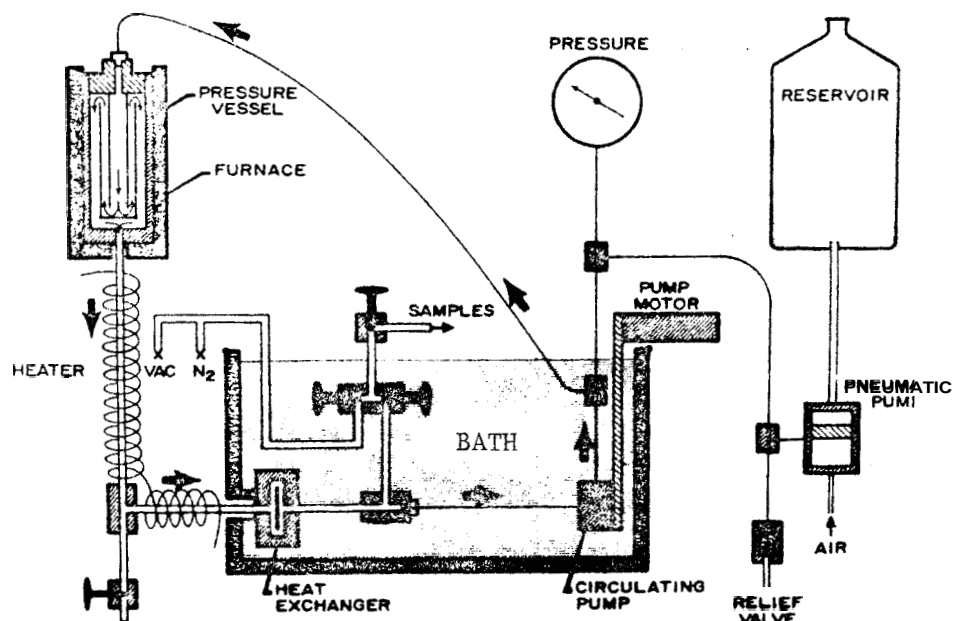


Fig. 5. Experimental system for determining reaction rates. In the 1 liter pressure vessel, either well characterized rock or mineral samples are held in circulating solutions at temperatures up to 450°C and pressures to 3500 p.s.i. Analyses of periodic samples of solution and of deposits in the heat exchanger, plus evaluation of alteration of the **rock** samples, permits determination of the principal reactions and the derivation of their rate constants.

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PREDICTING EXPLOSION-GENERATED PERMEABILITY
AROUND GEOTHERMAL WELLS

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The problem of stimulating geothermal reservoirs has received attention in recent years. Detonating explosives in a borehole is one technique for stimulating them. Explosives may also have an application where precipitation of solids near the producing well has significantly reduced the permeability around it. However, the enhancement of the permeability around the borehole has itself not been well-defined, and hence, the effects of explosive stimulation are difficult to predict. Below, we outline a theory which has correlated well with existing measurements of permeability enhancement. A more complete development can be found in Ref. 1.

Theory

The theory is based on linking the Carmen-Kozeny expression,

$$K \propto \frac{\phi^3}{(1-\phi)^2 S^2}, \quad (1)$$

with the parameters involved in the dynamic explosion process. In Eq. (1), ϕ is the porosity and S is the specific surface area.

To relate this formula to the complex phenomena of an explosive detonation, it is useful to view the explosion process in two stages.² The first stage is dominated by a large-amplitude stress wave. The second stage involves an expansion of the cavity by high-pressure gases from the detonation. The effects of the first stage on the media are of a dynamic nature, while those of the second stage extend over a much longer time interval and can be regarded as quasistatic processes. To obtain a description of permeability, we must relate these processes to Eq. (1).

According to Kutter and Fairhurst,² the principal role of the stress wave is to initiate fractures. The fracture density n is related to the porosity and specific surface by

$$n = \frac{S}{2w} (1 - \phi), \quad (2)$$

where w is the crack width. Griffith³ postulated a failure criterion for real materials. From tensile tests, he learned that the average stress at rupture was small compared with the theoretical strength of the solid.

He concluded that energy in the test piece was not uniformly distributed. At points where the cracks originate, high concentrations of strain energy must exist. We assume that these concentration points are macroscopic flaws in the material. A real geologic medium will contain a distribution of flaws having variations in length and orientation. Flaws may be naturally occurring fractures having a distribution in length and orientation, grain boundary weaknesses, and solution channels.

If similar specimens of a given material are subjected to failure tests, they do not all fail at the same stress. A distribution of breakage strengths will be found.⁴ It can therefore be interpreted that the material contains a distribution of flaw strengths. Variation in stress levels from an applied load at flaw tips is proportional to the square root of their lengths.⁵ Longer flaws will therefore have a higher probability of extending under a given applied stress.

The dynamic stress wave will cause all flaws whose strengths are less than the magnitude of the locally applied stress to extend. A relation between the growth of flaws or the increase in specific surface and energy can be obtained from comminution theory. Several comminution relations have been proposed. The one most applicable to our situation is Rittinger's Law, which states that an increase in specific surface area is directly proportional to the energy input:

$$S \propto E . \quad (3)$$

Rittinger's law has been substantiated by the general scaling laws of Langefors and Kihlstrom,⁶ which have been verified for burden dimensions varying between 0.01 and 10 m with a 10^7 variation in explosive charge.

Creating fractures does not in itself generate permeability. This is because the stress wave propagates at the compressional-wave velocity c_p , while fractures can grow in a rectilinear path at a maximum velocity $1/3 c_p$. Hence, the stress wave will inevitably outrun the fractures it generates. New fractures will then be initiated on other flaw sites in the material. At this moment in the process, the medium consists of a noninterconnected system of fractures with essentially no new porosity.

The second stage of the essentially continuous explosion process is dominated by the quasistatic expansion of the gas in the cavity. The cavity void space is produced by irreversible pressure-volume work of the explosive gases. Void space is created both by free-surface displacement and by compression of the surrounding rock. This model assumes that the fracture porosity surrounding the cavity is created by irreversible radial compression and the tangential tension of the surrounding rock. The fracture porosity will be proportional to the first invariant of the strain tensor,⁶

$$\phi \propto \Delta , \quad (4)$$

where Δ is the first invariant and contributes to porosity only when it assumes positive values (dilatation).

If we use the dynamic wave solutions of Selberg,⁷ the energy decay laws at the wave front are given by:

$$E \propto 1/r^2 \text{ (dynamic, spherical geometry)} \quad (5)$$

and

$$E \propto 1/r \text{ (dynamic, cylindrical geometry)} \quad (6)$$

If the static solution for a pressurized cavity is used, dilatation will be identically zero in both cylindrical and spherical geometries. However **rock** will exhibit bilinear behavior; and hence, the elastic moduli will have different values in tension and compression.^{8,9} Following the analysis of Haimson and Tharp,⁸

$$\Delta \propto \frac{(f-a)}{r^{1+a}}, \quad (7)$$

where $f = 2$ for spherical geometry and $f = 1$ for cylindrical geometry.

For well stimulation, the following appears to be a good approximation.¹

$$a = f - \epsilon, \quad (8)$$

where ϵ is a small positive number. Substituting (3), (5), (6), (7), and (8) into (1), and assuming the explosively generated porosity to be small, the functional behavior of the permeability in the linear elastic case will be approximately

$$k \sim 1/r^4 \text{ (cylindrical symmetry)} \quad (9)$$

and

$$k \sim 1/r^5 \text{ (spherical symmetry)} \quad (10)$$

Comparison with Experiment

There are only two known explosive stimulation experiments reporting extensive permeability measurements as a function of distance from the borehole. They are the 5 kt Hardhat nuclear event¹⁰ fired in granite, and the 59 kg chemical explosive detonated in coal near Kemmerer, Wyoming."

Fig. 1 shows the comparison between the theoretical expression [Eq. (10)] and the measured permeability around Hardhat. Fig. 2 shows the comparison between the permeability measured as a function of distance from the cylindrical cavity and Eq. (9) for coal.

Discussion

Despite a large variation in explosive yield and rock type between the Hardhat nuclear event and the Kemmerer coal experiment,

the predictions of the theory in both spherical and cylindrical symmetries are in excellent agreement with the experiments. No measurements are available for geothermal reservoirs. However, because of the agreement obtained to date, we believe that reasonable predictions can be made for specific geothermal reservoirs. For very deep applications, overburden stresses must be included to obtain the correct decay laws. Practical implementation will require careful evaluation of existing explosives for suitability and safety in the hot environment of geothermal reservoirs.

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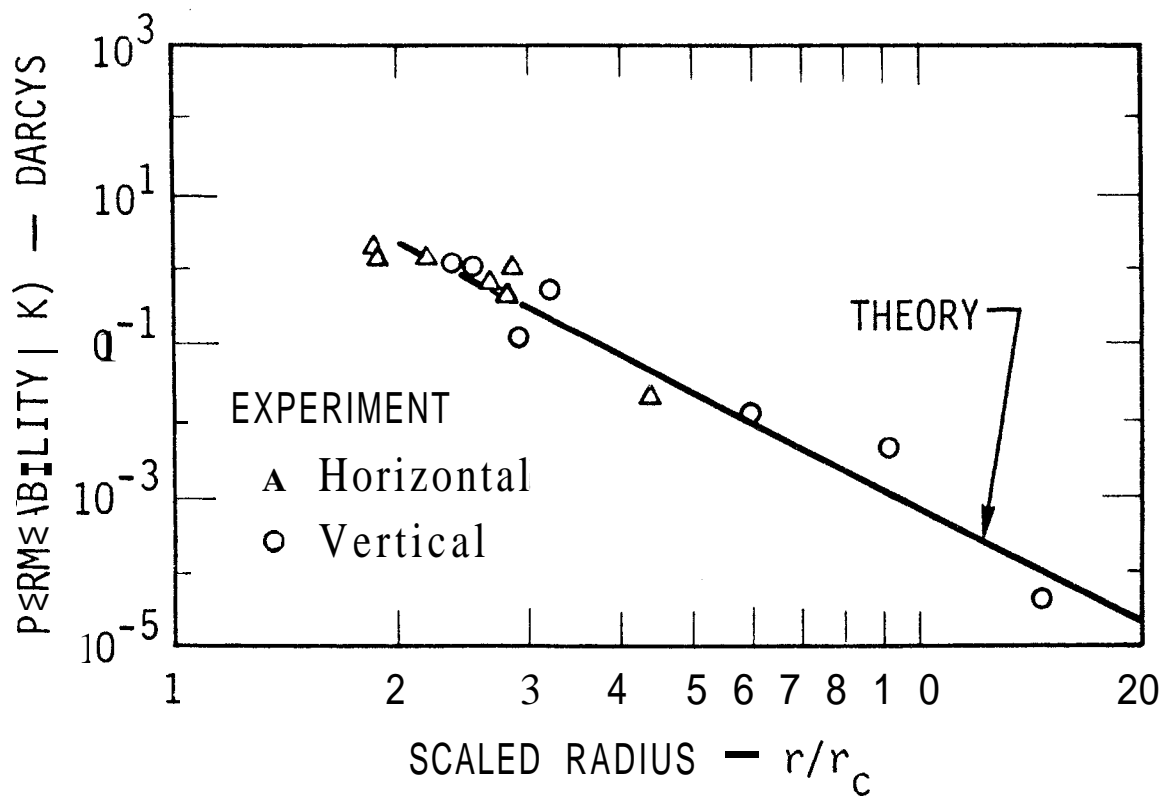


Fig. 1. Comparison of theoretical and measured permeability values. The log of permeability k is given as a function of distance scaled in terms of the cavity radius r_c . Permeability was measured in both horizontal and vertical holes, and is independent of direction.

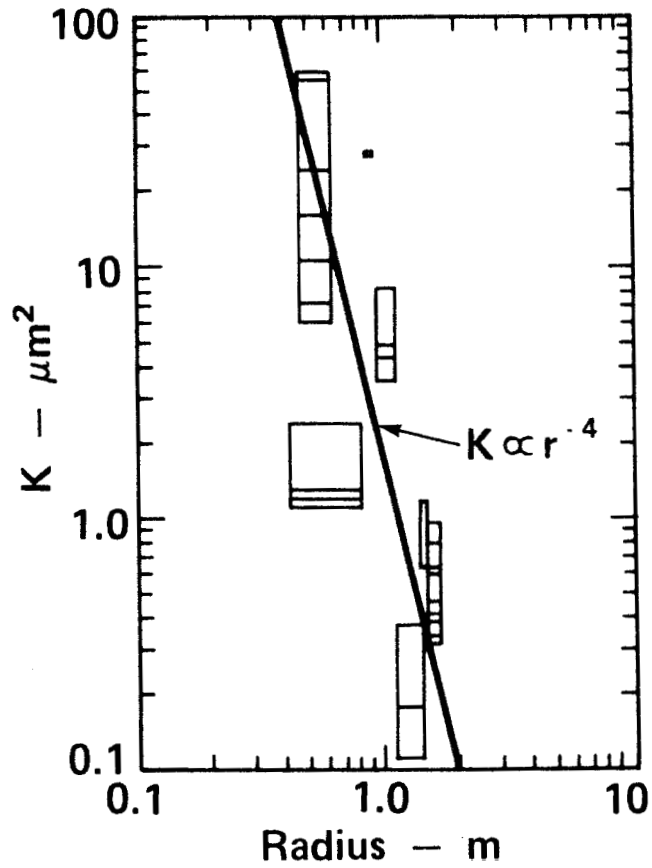


Fig. 2. Coal postshot permeability versus radius for a chemical explosive detonated in a coal seam. The emplacement geometry possessed cylindrical symmetry. Permeability is in Darcies, while the radial distance in meters is measured from the axis of the cavity. The small box on the upper right represents two measurements.

SUMMARY OF OUR RESEARCH IN GEOTHERMAL RESERVOIR SIMULATION

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Our research effort has concentrated on developing theoretical and numerical models for the purpose of simulating geothermal reservoirs. The first heat-transport model we developed was single-phase (liquid water), two-dimensional (areal), and was based on the Galerkin, finite-element method. This model was applied to the Wairakei geothermal field, which we were able to simulate until approximately 1962 at which time the reservoir became two-phase.

More recently we have formulated the equations of two-phase (steam-water), heat transport in terms of enthalpy and pressure.² Formulation of the basic mass, momentum and energy balances in terms of fluid pressure and enthalpy yields two nonlinear, partial differential equations that are valid for both liquid- and vapor-dominated hydrothermal reservoirs, as well as for reservoirs that may include both single- and two-phase regions. In addition, this formulation eliminates the interphase condensation terms.

Solution of these equations is performed using both finite-element and finite-difference techniques. The finite-element method is capable of using higher order elements, including Hermite cubics. Also, Newton-Raphson iteration may be used in both models (finite-difference and finite-element).

Model results for one- and two-dimensional problems have been compared with both analytical solutions and laboratory results.³ Hypothetical problems have been simulated and a sensitivity analysis of some parameters has been made.⁴ Results of these numerical experiments have given insight into the question of which numerical techniques are suitable for a particular geothermal reservoir problem. Based on these results, work on extending the Wairakei simulation has been initiated.

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THE PRINCETON GEOTHERMAL RESEARCH PROGRAM

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The research program currently underway in the Department of Civil Engineering at Princeton University can be subdivided into five separate interacting components. Each component addresses a specific problem encountered in the numerical simulation of geothermal reservoirs. In this summary, the components will be examined independently although in fact there are many facets of the work which overlap and thereby provide a foundation for the exchange of ideas between individuals.

The natural extension of the two-dimensional single phase areal model of the Wairakei reservoir is the fully three-dimensional problem. Although the development of a three-dimensional finite element energy transport code was relatively straightforward, the cataloguing, organization and manipulation of the large quantities of pertinent field data was more difficult. In preparing the input data trend surfaces of the important hydrological and geological parameters were generated. In this way the required information for each finite element node can be determined readily. The simulator is currently operational and the last elements of data are being prepared.

While the correct formulation of the equations governing multi-phase (steam-water) flow in porous media is now available in the literature, the development of an accurate and efficient three-dimensional simulator still remains a formidable task. Because of the flexibility and accuracy of the finite element-Galerkin approach, this method has been chosen as the basis for our general simulator. To overcome limitations inherent in the classical finite-element approach, highly efficient coefficient generating schemes are combined with iterative methods for the solution of the resulting large systems of algebraic equations.

Although the Biot system of equations based on the theory of elasticity is generally recognized as a rigorous expression of the physics of subsidence, it does not describe important phenomena observed in the field. In particular, it is observed that physical systems are characterized by parameters which exhibit memory. A correct formulation of the problem, therefore, must be based upon visco-elastic rather than elastic theory. Because of the lack of understanding of the exact form of the stress-strain relationship, we have assured generality by considering an approach which extracts the form of this equation directly from available laboratory experiments rather than dictating it a priori. The resulting system of equations is solved using the Laplace transform in conjunction with a finite element-Galerkin scheme.

Although equations for energy transport in porous media have been in use for some time, we deemed it necessary to verify that these equations had a sound theoretical basis. A systematic technique of local volume averaging

of the continuum equations was adopted and applied to the thermal energy equation. This technique allows one to derive an equation for each phase which contains terms accounting for mechanical dispersion, interphase energy conduction and phase change.

When the assumption of thermal equilibrium between the various phases is reasonable, the equations for each phase may be added together and the coupling terms between the phases will drop out. However, if conditions are such that thermal equilibrium is not established, appropriate constitutive relations can be found for the coupling term and the equations are solved separately for each phase.

For the case of cold water injection into a fractured geothermal reservoir, one might expect the cold water to move at different velocities in the fractures and pores and thermal equilibrium between the pore and fracture fluid may not exist. To model this case, the pore fluid and fracture fluid were considered to be different phases and flow and energy equations were developed for each of the two fluid phases as well as for the solid matrix. At present, a Galerkin-finite element computer code is being developed which solves the complete coupled set of equations. The unknown variables are expanded in terms of a new type of basis function which allows for increased accuracy and a reduction in the number of finite element equations which must be solved.

NUMERICAL CALCULATION OF MULTIPHASE FLUID AND HEAT FLOW
IN HYDROTHERMAL RESERVOIRS

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In this paper one aspect of an ongoing research program will be described. The overall objective is to develop reliable computer simulators whereby field information for a specific liquid- or vapor-dominated geothermal system can be used to predict reservoir performance and, in addition, subsurface environmental effects. These latter effects include land surface subsidence, induced seismic activity, and pollution of fresh water aquifers by geothermal brines. The approach is to develop large-scale computer programs and to validate them using both laboratory measurements and field data.

So far, separate codes have been developed for describing the multidimensional multiphase unsteady flow of steam and water and of heat in a heterogeneous geologic setting in the absence of rock deformation, and for calculating the response of a multidimensional rock matrix to prescribed pore pressure changes without specific consideration of fluid flow. These codes are presently being combined to produce a single fully interactive fluid flow/rock deformation simulator. The separate codes in themselves may be of some interest, however; S. K. Garg discussed the finite-element rock-deformation simulator in another presentation at this workshop. Here, the fluid-flow simulator will be discussed.

Mathematical Formulation

Brownell ~~et al.~~ (1975) have presented elsewhere the equations governing the flow of water and steam in a non-deforming rock matrix. These may be summarized as follows:

Fluid Mass Conservation:

$$\phi \frac{\partial \rho}{\partial t} = \dot{m} + \nabla \cdot \left[k \left([\alpha_L \rho] [VP - \rho_L \vec{g}] + [\alpha_V \rho] [VP - \rho_V \vec{g}] \right) \right]$$

Energy Conservation:

$$\frac{\partial}{\partial t} [E_S + \phi E] = \dot{e} + \nabla \cdot \left[k \left([R_L E] [VP - \rho_L \vec{g}] + [R_V E] [VP - \rho_V \vec{g}] \right) + \bar{\kappa} \nabla T \right]$$

Local Thermal Equilibrium:

$$T_S = T$$

where

	$S = 0$ (all liquid)	$0 < S < 1$ (multiphase)	$S = 1$ (all vapor)
α_L	$1/\mu$	$\frac{1-Q}{1-S} \frac{R_L}{\mu_L}$	0
α_V	0	$\frac{Q}{S} \frac{R_V}{\mu_V}$	$1/\mu$
β_L	$1/\mu$	$\alpha_L [1 - Q E_{\text{vap}}/E]$	0
β_V	0	$\alpha_V [1 + (1-Q) E_{\text{vap}}/E]$	$1/\mu$

and

- E = Bulk fluid internal energy per unit fluid volume.
- E_{vap} = Latent heat of vaporization per unit fluid volume.
- E_S = Solid internal energy per unit total volume.
- ρ = Bulk fluid density.
- ρ_V = Vapor phase density = $\rho Q/S$.
- ρ_L = Liquid phase density = $\rho(1-Q)/(1-S)$.
- Q = Steam quality.
- S = Steam saturation.
- $\mu(\mu_L; \mu_V)$ = Bulk fluid (liquid; vapor phase) viscosity.
- $R_V(R_L)$ = Relative vapor (liquid) permeability.
- k = Absolute solid permeability.
- $\bar{\kappa}$ = Mixture (rock-liquid-vapor) heat conductivity.
- ϕ = Porosity.
- P = Pressure.
- T = Fluid temperature.
- T_S = Solid temperature.
- \vec{g} = Acceleration of gravity.
- \dot{m} = Local fluid mass source/sink rate.
- \dot{e} = Local heat source/sink rate.

These balance laws are to be solved subject to appropriate initial and boundary conditions. Furthermore, constitutive relations must be prescribed both for the rock matrix and for the institial fluid. For the rock, the density, porosity, directional absolute permeabilities, relative permeability functions, heat capacity and thermal conductivity must be supplied at each point in the system. For the fluid, a large number of properties must be known as functions of water density (ρ) and internal energy (E). These include pressure (P), temperature (T), steam quality (Q), vapor saturation (S), latent heat of vaporization (E_{vap}), and separate viscosities (μ_l, μ_v) and thermal conductivities (κ_l, κ_v) for liquid and vapor. For this purpose, a rather elaborate system of subroutines was developed which uses large data tables and various interpolation schemes valid up to ultra-high pressures (several megabars) and temperatures to 3000°C.

Computer Code and Applications

The system of balance equations is solved by a finite difference technique which has been described elsewhere (Pritchett *et al.*, 1975). Essentially, an implicit-time, first-order (upstream) space representation of the equations is employed; the iterative Alternating-Direction-Implicit (ADI) technique is used to reduce a single multidimensional problem to an equivalent sequence of one-dimensional problems. These one-dimensional problems are, of course, nonlinear in themselves--these nonlinearities are removed by iteration within the one-dimensional "module."

The numerical scheme has been incorporated into a simulator which possesses considerable flexibility. Several geometries can be considered: (1) 1-D slab, (2) 1-D cylindrical, (3) 1-D spherical, (4) 2-D planar or areal, (5) 2-D axisymmetric, or (6) 3-D Cartesian. Each computational zone may contain a different rock type, and any face of any zone may be a boundary. Provision is made for all practical boundary condition options: (1) impermeable, insulated, (2) impermeable, prescribed heat flux, (3) impermeable, prescribed temperature, (4) prescribed mass flux, insulated, (5) prescribed mass and heat flux, (6) prescribed mass flux and temperature, and (7) prescribed pressure and fluid heat content. Boundary condition parameters may be functions of time.

The simulator has been extensively tested, using both simplified analytic problems with known solutions and bench-scale experimental results. Work is currently in progress to simulate the field production history at the Wairakei field in New Zealand. Garg, *et al.* (1975) presented some of the test results against laboratory data at the United Nations Conference in San Francisco last May. Briefly, one-dimensional simulations were performed of laboratory experiments carried out by Kruger and Ramey (1974) and Arihara (1974) at Stanford. These experiments involved flow in a narrow 60 cm long tube packed with sandstone. In these experiments, non-isothermal and multiphase flow occurred. Results computed by the simulator included pressure and temperature distributions within the tube as functions of time--agreement was generally within experimental scatter for all cases considered.

This numerical reservoir simulator is therefore considered operational and possesses several desirable features. Mass and energy are conserved exactly, since the numerical scheme is based squarely upon density and internal energy rather than other auxiliary quantities. Proper treatment of flow-type (i.e., prescribed-pressure) boundaries eliminates artificial computational "energy sources" at these boundaries, even under conditions of flow reversal. The use of the implicit upstream difference technique suppresses the computational "jitter" produced by many other simulators--artificial oscillations of this sort occasionally cause computational catastrophes in single-phase regions near the saturation line.

A recent paper by Coats ~~et al.~~ (1973) describes a serious computational difficulty they encountered when performing a 2-D areal simulation of a five-spot steamflood of an oilfield. The "five-spot" pattern is a checkerboard-like system with alternating injection and production wells. Coats found that if he treated this problem with a grid oriented such that a line connecting adjacent production and injection wells lies at 45° with respect to the axes the computed water interface expands outward in a roughly circular manner, whereas if the grid is oriented with coordinate lines connecting adjacent production and injection wells, thin "fingers" of injected fluid penetrate outward rapidly. Times of water breakthrough at the production well differed by a factor of three for these calculations. To investigate this problem, our geothermal reservoir simulator was used to calculate a five-spot cold water injection into a producing hot-water field, using both grid orientations. Times of cold water breakthrough computed in these two calculations agreed within a few percent, which is less than the resolution of the finite-difference grid employed. Therefore, it is believed that the present method is not subject to this difficulty, at least for problems of geothermal interest.

Several applied calculations have been performed so far using the simulator. One series of computations reported at the United Nations Symposium by Garg et al. (1975) show that, in a bounded geothermal reservoir with no internal or external heat or mass sources, reinjection of waste water will substantially augment the producing life and the total energy deliverability of the system. At present, under a parallel in-house project, a series of calculations are underway which illustrate the effect of information flashing upon wellhead pressure histories during drawdown and shut-in well testing (Rice, 1975). As mentioned earlier, a simulation of the Wairakei system is now being undertaken.

Coupling of the simulator with the rock-response finite-element code is now in progress. Completion of this task will permit more accurate seismic and subsidence predictions, and will also aid in extending our capability to include cases wherein rock composition produces a significant fraction of the reservoir drive (such as the geopressured systems of the Gulf Coast). Also in progress is the extension of the water equation of state to consider brines, and the addition of a solute-conservation equation to the simulator. These features are desirable when considering very saline systems such as the Salton Sea geothermal field.

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METHODS OF SOLUTION OF THE EQUATIONS FOR CONVECTION
IN POROUS MEDIA, WITH GEOTHERMAL APPLICATIONS

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Various approaches to the solution of the equations of thermal convection in fluids may be classified, for convenience, under such headings as: (1) the Stuart-Watson method, which deals with the behavior of finite-amplitude instabilities, for which $R/R_c = 1$, where R is the Rayleigh number and R_c is its critical value for neutral stability; (2) the Galerkin method, a well-known numerical technique utilizing truncated expansions in orthogonal functions, which has been applied up to $R/R_c \approx 0(10)$; (3) the variational method, which seeks to establish bounds on the heat transport, for given Rayleigh number, up to large R/R_c ; (4) direct numerical solution of the convection equations, usually in finite-difference form, up to $R/R_c \approx 0(10)$.

These techniques are considered in relation to the equations of convection of variable-viscosity fluid in a porous medium.

Since the particular application is intended to be geothermal convection, many simplifications may have to be accepted. First, it is assumed that the flow can be treated as flow through porous media. This is not necessarily true, although the approximation becomes more satisfactory if only large-scale motions are considered. Secondly, the medium may not be isotropic. This is not a serious difficulty, but isotropy will be assumed for convenience. Thirdly, salt may be transported as well as heat, and can exert an influence upon fluid buoyancy. Evidently, the transport of salt would involve a straightforward generalization of the treatment for heat transport (although some new phenomena are encountered), and is not considered here. Fourthly, chemical interaction of the fluid with the medium, which would introduce great complications, is assumed to be negligible.

Very large temperature differences are encountered in geothermal applications, so that the dependence upon temperature of fluid properties needs to be taken into account. The most important of these is the variation of viscosity, which may involve an order-of-magnitude change. The fluid and porous medium are assumed to be incompressible, but dilation and contraction of the fluid with temperature changes may lead to a 20% change in density, which is of some significance. This is most readily taken into account, while retaining a convenient form of the equations, by introducing a vector \underline{q}_m proportional to the mass flow rate, and relating this to the volume flow rate \underline{q} by

$$\rho_0 \underline{q}_m = \rho \underline{q} \quad (1)$$

Here ρ is the fluid density at temperature T , and ρ_0 is a density

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corresponding to a reference temperature T_0 . Then the equations of continuity, motion and heat transport take a convenient form (c.f. Wooding, 1957, 1960):

$$\frac{\epsilon}{\rho_0} \frac{\partial \rho}{\partial t} + \nabla \cdot \underline{q} = 0 \quad (2)$$

$$\frac{1}{\rho_0} \nabla P - \underline{kg} \frac{\rho}{\rho_0} + \frac{\nu}{k} \underline{q} = 0 \quad (3)$$

$$E \frac{\partial T}{\partial t} + \underline{q}_m \cdot \nabla T = \kappa \nabla^2 T \quad (4)$$

Here t is time, P is pressure, E is the porosity of the medium,

$$E = \{(1 - \epsilon)c_s \rho_s + \epsilon c_f\} / c_f \rho_0 \quad (5)$$

is the ratio of the heat capacity per unit volume of saturated medium (at temperature T) to that of the fluid (at temperature T_0), c signifies specific heat and suffix s denotes the solid medium. Also, k is the intrinsic permeability, ν is the kinematic viscosity of the fluid, κ is the thermal diffusivity of the saturated medium, here taken constant, g is the magnitude of gravity and \underline{k} is a unit vector, directed vertically upwards. While Equations (2) and (4) are straightforward conservation relations, Equation (3) (Darcy's Law) is a force-flux relation which involves some assumptions--notably the existence of the permeability k .

In addition to the foregoing, there must exist an equation of state for each temperature-dependent quantity. Here the relation for density often is taken as

$$\frac{\rho - \rho_0}{\rho_0} = - \frac{T - T_0}{\alpha T_0} \quad (6)$$

i.e., the Boussinesq approximation, α being the temperature coefficient of linear expansion of the fluid. Thermal expansion of the medium is neglected. A more satisfactory representation of the thermal expansion law requires a polynomial.

The variation of viscosity with temperature is quite strongly non-linear. For geothermal applications a simple relation for water is

$$\underline{\nu} = \nu_0 \{1 + a (T - T_0)\}^{-1} \quad (7)$$

where the coefficient a may be 0(10) (Wooding, 1957). This constitutes one of the main obstacles to the direct use of some of the standard methods of solution of **the** convection equations.

A further important source of nonlinearity is the term $q_m \cdot \nabla T$ in (4). Since most convection studies in the literature correspond to the case of constant viscosity, the latter nonlinearity has received considerable attention, whereas the particular situation of variable viscosity has received relatively little.

In viscous-fluid convection, the important case of a small variation of viscosity has been treated by perturbation methods by Palm (1960), Segel and Stuart (1962), Palm and Øiann (1964), Segel (1965a, b) and others, with considerable success, since the reason for the existence of hexagonal convection cells over a finite range of Reynolds number has been satisfactorily explained.

An equivalent analysis for flow in porous media has not been carried out, as far as is known. However, most cases of interest in porous-media flow, particularly with geothermal applications, involve very large changes of viscosity, for which a perturbation analysis on the above lines would not be satisfactory. Generally, it is considered necessary to resort to numerical techniques, as in papers by Wooding (1957, 1963) and recent studies by Horne (1975) and Kassooy and Zebib (1975), or by the use of variational techniques (e.g., Wooding, 1960, 1975).

Techniques of Solution of the Convection Equations

A convenient classification is the following:

1. The Stuart-Watson Method (Stuart, 1958; Watson, 1960; Stuart, 1964; etc.) is used for treating finite-amplitude instability problems, i.e., to find answers to the question: What happens to an infinitesimal disturbance as it grows to finite amplitude in a situation which is linearly unstable? Clearly, a single disturbance mode will, through nonlinearities, generate a "normal-mode cascade" (Segel, 1965c) and these in turn will interact to modify the fundamental disturbance amplitude. Generally the effect is to introduce nonlinear damping of the fundamental, so that the disturbance grows to a finite amplitude and a new stable equilibrium results. However, special cases of reinforcement (e.g., resonance) may be encountered.

Since the Stuart-Watson method involves expansion in normal modes about the neutral disturbance, and the expansion is truncated after the third-order terms (c.f. Segel, 1965a), it is limited to flow situations where the amplitude remains small (although finite) throughout all time. This generally restricts its use in convection problems to cases where the Rayleigh number $R \approx R_c$ -- the critical value for neutral stability. In spite of this limitation, the method yields great physical insight into mechanisms of fluid instability.

2. The Galerkin Method (Veronis, 1966; Straus, 1974; Clever and Busse, 1974; etc.) is one of the oldest and best known. Briefly, expansions of the dependent variables in the convection equations are sought in terms of orthonormal functions which satisfy the boundary conditions term by term. The method of truncation of these series, first described by Veronis, is to

choose a "maximum total wavenumber," i.e., to retain only those terms for which the sum of the wavenumbers in the various spatial directions does not exceed a given upper bound. When the differential equation is linear, it is possible to obtain relationships between the coefficients by term-by-term comparison. Otherwise each partial differential equation may be reduced to a set of ordinary differential equations (say in time) or an algebraic equation, by multiplying by successive terms of the orthonormal set, and integrating over space. The resultant set of ordinary differential equations, or of algebraic equations, can then be solved by conventional numerical methods.

For the case of two-dimensional convection in a porous medium with constant viscosity, Straus (1974) has calculated the dependence of Nusselt number (Nu) upon Rayleigh number up to $R \approx 380$, above which point (from linearized stability analysis), two-dimensional solutions are unstable. For $R > 100$, the (R, Nu)-curve shows a significant change in slope. The results are in good agreement with experimental measurements.

3. The variational method of Howard (1963) and Busse (1969) has been used by Busse and Joseph (1972) and Gupta and Joseph (1973) to calculate upper bounds to the Nusselt number, as a function of Rayleigh number, for three-dimensional convection in a porous medium at constant viscosity. In this approach, the equations of motion and heat transport are recast as a variational problem, involving averages over the entire porous layer. Then the dependent variables appearing in the variational problem are replaced by a "class of admissible functions" which includes all statistically stationary solutions, and which satisfies the boundary conditions and any supplementary conditions which may be specified. The Euler equations of the variational problem embrace a wide class of solutions, corresponding to extreme values of the system, and these may be represented by expansions in orthonormal functions based upon horizontal wavenumbers α_n . A single wavenumber is adequate up to $R = 221.5$ (Gupta and Joseph, 1973), at which point the solution bifurcates and two α -values are needed. These calculations have been carried up to about $R = 500$ with very good agreement with experiment. At higher R , an asymptotic (boundary-layer) analysis based on that of Chan (1971) predicts appropriate qualitative behavior, but these results are not in good quantitative agreement with the numerical studies.

4. Methods of numerical solution of the convection equations are now the subject of a very large literature, and extensive reviews such as those by Orszag and Israeli (1974), or of Horne (1975) for porous media, are necessary to ensure adequate treatments. Because of limitations in computer capacity and speed, most convection studies have been limited to two-dimensional flows. Convection in viscous fluids with large variations in viscosity has been considered, for two-dimensional flows, by Torrance and Turcotte (1971) and by Houston and De Bremaecker (1974).

Horne (1975) has carried out some calculations with variable viscosity for two-dimensional convection in porous media. In discussing his results, Horne comments that equally-vigorous convection occurs with variable viscosity at lower apparent Rayleigh number than in the constant-viscosity case, since R is defined for $T = T_0$, where viscosity is high. He also

observes that the representation of a variable-viscosity convection system with a constant-viscosity model is "inexact, but not entirely without use." This suggests that an intermediate value of Rayleigh number might be found which corresponds to the constant-viscosity value at the same Nusselt number. However, in studying the onset of convection in porous media with variable viscosity, Kassoy and Zebib (1975) conclude that the viscosity variations have substantial effects upon the flow pattern and that a mean value of viscosity cannot be taken to estimate a suitable intermediate value of R .

Numerical studies of convection in three dimensions in a viscous fluid, based on the early work of Chorin (1966), have been performed by Veltishchev and Zelnin (1975), taking viscosity constant. In this approach the equations are represented in finite-difference form, using "primitive" variables, i.e., velocity components (u, v, w), temperature and pressure. Calculations were carried out in a rectilinear domain with horizontal dimensions 2.34 and 4.03 times the depth. (In common with other numerical models, the domain is limited to a finite box.) Interesting stable convective flow patterns are obtained, notably two-dimensional rolls for low to intermediate values of the Rayleigh number, three-dimensional flows in a higher, somewhat narrower, range, and unsteady motions above that. These flow transitions are accompanied by changes in slope of the Rayleigh number-heat flux curve.

For three-dimensional Convection in a porous medium, relatively few references can be found. Holst and Aziz (1972) used a combination of successive over-relaxation for the solution of the equation of motion (reduced to Poisson's equation) with centered differencing for the first derivations of the heat equation. However, the more advanced techniques of direct solution utilized by Horne and O'Sullivan (1974) and Horne (1975) are faster and more accurate. These employ an Arakawa (1966) finite-difference scheme to evaluate the terms arising from $g_m \cdot \nabla T$ in (4), and an extension of the Buneman algorithm (Buzbee, Golub and Nielson, 1970) to evaluate the Poisson equation. Horne (1975) has used these techniques to calculate solutions for three-dimensional convection in a cubical box, taking a $17 \times 17 \times 17$ mesh, at $R = 500$. For a uniformly heated lower boundary, convection is found to take the form of two-dimensional rolls, even when the initial perturbation is three-dimensional.

It is planned to publish a more detailed treatment at a later date.

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A HELE-SHAW MODEL OF HEAT CONVECTION IN POROUS MEDIA
UNDER GEOTHERMAL CONDITIONS

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Evidence from New Zealand indicates that geothermal fields occur at reasonably regular intervals of about 15 kilometers apart. Investigators have speculated that these regular intervals may be indications of the scale of the heat convection cells.

Wooding (1975) has described the four well-known approaches to solve the equations of continuity, motion and heat transport for heat convection in porous media. Unfortunately, to date, none of these methods has provided solutions for all geothermal conditions with a Rayleigh number up to the order of 1000 and also allowed the viscosity to vary. In New Zealand, the permeability is in the order of 3×10^{-11} cm², the change of density $\Delta\rho$ is 0.2 gm/cm³, the length scale L is about 5×10^5 cm, the dynamic viscosity μ is 0.001 to 0.01 poise (depending on the temperature of the fluid) and the thermal diffusivity k is 0.003 cm²/sec. The range of Rayleigh number would be from 100-1000.

The Stuart-Watson method has been applied to small viscosity change and low Rayleigh number ($R \sim R_c$ the critical value for neutral stability). For high Rayleigh number the method is not applicable. The Galerkin method has been applied to two-dimensional constant viscosity cases. The variational method has been applied to three-dimensional constant viscosity cases with $R \sim 500$. The methods of numerical solution have been applied to both constant and variable viscosity cases. Due to the great cost involved in computer solution, a relatively large mesh was used at $R = 500$. The accuracy of these results is questionable.

Since none of these above-mentioned equations can provide solutions for variable viscosity in high Rayleigh number regions, physical models are particularly attractive at this stage. If properly designed, physical models should provide (1) approximate final solutions; (2) verification of numerical and analytical solutions; (3) a solution obtained from keeping variable-viscosity terms in the equation versus a solution obtained from assuming constant viscosity in the equation; and (4) change of solution forms with increased Rayleigh number.

Analysis

Two-dimensional experiments cannot fully represent the three-dimensional situation of a geothermal region, but they are useful to demonstrate the influence of large variations of viscosity on the form of convecting plumes of hot water.

For two-dimensional convection in the (x,z) plane, the usual stream-function representation

$$\underline{u} = \left(\frac{\partial \psi}{\partial z}, -\frac{\partial \psi}{\partial x} \right) \quad (1)$$

gives, after eliminating pressure from Darcy's law,

$$\frac{\partial}{\partial x} \left(\sigma \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial z} \left(a \frac{\partial \psi}{\partial z} \right) = \frac{\partial \theta}{\partial x} \quad (2)$$

where θ is a dimensionless fluid density, and $a = (\mu/k)/(\mu/k)_0$ is a dimensionless viscosity parameter. The suffix 0 refers to the lowest temperature in the system. Typically, a will vary from 1 at the cold end of the range to about 0.1 at the hot end--an order-of-magnitude change.

A further equation describes heat or mass transport

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial \tau}{\partial x} \frac{\partial \psi}{\partial z} - \frac{\partial \theta}{\partial z} \frac{\partial \psi}{\partial x} = \frac{1}{R} \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial z^2} \right) \quad (3)$$

where

$$R = \frac{k_0 g \Delta \rho L}{\mu_0 \kappa} \quad (4)$$

is the Rayleigh number. Also, in (3) τ is a dimensionless time defined by

$$\tau = \frac{kg\Delta\rho \cdot t}{\mu_0 EL} \quad (5)$$

The parameters in (4) and (5) are defined in terms of the problem under study. k_0 is the permeability of the medium, g is gravity, $\Delta\rho$ is the density difference between hot and cold, μ_0 is the viscosity of the cold fluid, κ is the diffusivity of the density-controlling property, and L is a length scale--typically the depth in the case of a saturated porous layer in which convection is taking place, $E = \{(1-n) c_s \rho_s + n c_p\}/c_p$ is the ratio of the heat capacity of the medium to that of the fluid. The suffix s refers to the medium.

Two-dimensional systems governed by the above equations may be solved, for example, by physical modelling or by computer methods.

Description of Hele-Shaw Model

A typical physical model of two-dimensional convection is shown in Fig. 1 below. A Hele-Shaw cell is formed from two strips of 1/4-inch thick polished plate glass, separated by strips of waterproof adhesive tape. In the example shown, a cavity 20 cm x 1 cm is formed in the (x,z) plane. The thickness of the cavity is very small so that a slow viscous flow occurs between the plates. The flow averaged between the plates is analogous to two-dimensional flow in a porous medium of permeability $k = d^2/12 \text{ cm}^2$, where d is the plate spacing.

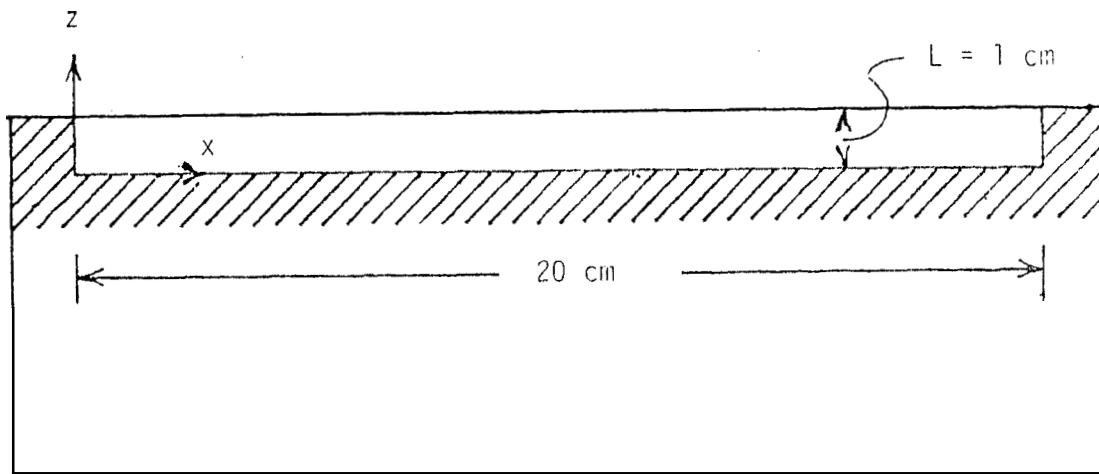


Figure 1. Plan View of Hele-Shaw Cell

The cell is mounted with the x-axis horizontal, and with the z-axis at an angle α to the horizontal so that the effective gravity component is $g \sin \alpha$. This is useful for adjusting the Rayleigh number R to a desired value.

In the case shown, the cell is filled with a fluid of density and viscosity μ_1 (say) which represents a geothermally heated fluid. ρ_1 The cell is immersed in a transparent tank filled with fluid of density ρ_0 and viscosity μ_0 , representing cold groundwater.

Since the width of the cell is very large compared with L , the sidewall boundary conditions will be ignored. The following initial and boundary conditions are taken to apply:

$$w = 0, \theta = 0 \quad (t = 0, 0 \leq z \leq 1) \quad (6a)$$

$$w = \varepsilon(x), \theta = 1 \quad (t = 0, z = 1) \quad (6b)$$

where w is vertical velocity, $\varepsilon(x)$ is a small noise signal,

$$w = 0, \frac{\partial \theta}{\partial z} = 0 \quad (t > 0, z = 0) \quad (7a)$$

(insulating impermeable boundary condition)

$$\frac{\partial w}{\partial z} = 0, \theta = 1 \quad (t > 0, z = 1) \quad (7b)$$

(constant pressure, constant density, boundary condition).

These conditions could correspond to a geothermal field situation where a period of volcanicity has injected a large amount of heat, in the form of magmatic steam, into a deep groundwater aquifer, so that the whole aquifer is initially very hot. After the volcanicity has quieted down, cold surface water intrudes from above, displacing the hot water which appears at geothermal areas.

The experiment is aimed

- (1) To model the deep groundwater motion (at least in two dimensions) which is not accessible to geophysical observation at the present time,
- (2) To provide an experimental relationship between the heat flux out of the region (expressed as the Nusselt number) and the Rayleigh number.

It is necessary that the fluid initially in the cell be marked with a dye so that convective motions may be photographed and studied. This colored fluid can also be used for photometric work--to determine how much of the initial fluid has been displaced from the cell and so arrive at estimates for the Nusselt number, at various values of the Rayleigh number.

Field values of parameters based upon measurements in the Taupo Volcanic Zone, particularly Wairakei geothermal field, give the following approximate results:

$$\begin{aligned}
 \text{Permeability } k \text{ (vertical)} &= 3 \times 10^{-11} \text{ cm}^2 \\
 \text{Density difference } \Delta\rho &= 0.2 \text{ gm/cm}^3 \\
 \text{Vertical scale } L &= 5 \text{ Km} \\
 \text{Cold water viscosity } \mu_0 &= 10^{-2} \text{ poise} \\
 \text{Thermal diffusivity } \kappa &= 3 \times 10^{-3} \text{ cm}^2/\text{sec} \\
 R = \frac{kg\Delta\rho L}{\mu_0 \kappa} &\approx \frac{3 \times 10^{-11} \times 10^3 \times 0.2 \times 5 \times 10^5}{10^{-2} \times 3 \times 10^{-3}} = 100
 \end{aligned}$$

For the time constant based upon cold water viscosity, $E \approx 1$, and

$\frac{1}{R} \frac{EL^2}{\kappa} \approx 10^{12}$ seconds or roughly 30,000 years. However, since the hot water viscosity $\mu_1 \approx 0.1 \mu_0$, the Rayleigh number based on this value would be roughly 1000, and the time constant would be reduced to the order of 3000 years. It seems likely that the flow pattern would exhibit some properties of both high and low Rayleigh number.

In two recent experimental runs using sucrose solutions in the Hele-Shaw cell, the parameters were approximately as follows:

	<u>Run No. 3</u>	<u>Run No. 4</u>
L	1 cm	1 cm
k	$2.63 \times 10^{-5} \text{ cm}^2$	$2.63 \times 10^{-5} \text{ cm}^2$
ρ_0	1.28 gm/cm ³	1.28 gm/cm ³
μ_0	0.5 poise	0.5 poise
ρ_1	1.16 gm/cm ³	1.225 gm/cm ³
μ_1	0.05 poise	0.167 poise
μ_0/μ_1	10	3
κ	$0.3 \times 10^{-5} \text{ cm}^2/\text{sec}$	$0.3 \times 10^{-5} \text{ cm}^2/\text{sec}$
$\Delta\rho$	0.12 gm/cm ³	0.055 gm/cm ³
α	6°.5	3°.5
R	250	50
E	1	1
$\frac{1}{R} \frac{EL^2}{\kappa}$	0.37 hour	1.5 hours
$\tau(\text{max})$	74	49

The second-last entries in this table are the cold-water time scales, while the final entries, $\tau(\text{max})$, are the maximum values of dimensionless time achieved experimentally.

It is interesting to note that $\tau = 50$ corresponds to an elapsed time of 1.5 million years on the prototype cold-water time scale, or 150,000 years on the hot-water time scale. These figures bracket the estimated life of the geothermal activity in the Taupo Volcanic Zone. It follows that the hypothesis of a phase of initial volcanism is not contradicted by experiment, which shows that plumes of hot water are still present at $\tau = 50$.

As a supplement to Run No. 4, at $R = 50$ and $\mu_0/\mu_1 = 3$, a computer run was made using a program which solves the convection equations by finite-difference methods. This program is due principally to Dr. M. J. O'Sullivan, of the University of Auckland, but has been modified to include a modest variation of viscosity and also to compute transport of dissolved salt. The development of convective plumes in the computer run, for convection in a rectangle of width:height ratio 4, is qualitatively similar to that observed in the physical model. However, there has not been time to make detailed comparisons, especially of Nusselt numbers.

The entire study is based on the assumption of homogeneous geological conditions which is normally not valid. By varying the size of the gap between the plates and by placing sources and sinks in the flow, different geological conditions may be simulated. This is planned for future studies.

Acknowledgment

This model was suggested to the author by Dr. Robin Wooding, and we are jointly conducting this research project.

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NUMERICAL AND ANALYTICAL STUDIES ON HEAT AND MASS TRANSFER
IN VOLCANIC ISLAND GEOTHERMAL RESERVOIRS

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The Hawaii Geothermal Project is a multidisciplinary research effort with the major objectives of locating a suitable geothermal resource on the island of Hawaii and utilizing the heat to produce electricity by means of a research-oriented power plant. As a primary first step of this project, the potential geothermal resources on the island of Hawaii must be studied and sufficient information obtained to permit a reasonable prediction to be made of the behavior of the geothermal field, as well as the environmental impact of the utilization of the resources.

The Hawaiian Islands were formed by volcanic action. Because of the high porosity and permeability of the basaltic formation, aquifers at shallow depth are likely to be unconfined from the top. It has been postulated that a magma chamber at shallow depth and the numerous hot intrusives that form a dike complex can provide the heat source for the heating of the groundwater in the aquifer (Furumoto 1975). As the high permeability of the formation permits a continuous recharge from the ocean and rainfall, it has been speculated that most of the geothermal resource at shallow depth in the island is probably warm water at low or moderate temperatures (Macdonald 1973). Because of a self-sealing effect it is possible that impermeable layers are formed at great depth where hot water may be found (Furumoto 1975). As the basaltic rock hardly deforms under pressure, a large scale land surface subsidence resulting from the withdrawal of geothermal fluids is not anticipated. However, the utilization of geothermal resources in the island is not free from other adverse environmental impacts. The most serious potential hazard is the possibility of the contamination of the freshwater lens during the reinjection of the toxic fluids into the formation. The prediction of the fate of the injected fluids under different operating conditions thus merits careful consideration.

The following is a summary of the progress we have made in the past two years on the theoretical study of heat and mass transfer in a volcanic island geothermal reservoir. Many of the results are of a fundamental nature and are, therefore, applicable to other liquid-dominated reservoirs.

Numerical Studies on Heat and Mass Transfer in
Liquid-Dominated Geothermal Reservoirs

Free Convection in Island Geothermal Reservoirs. The problem of steady free convection in an island aquifer, confined by caprock at the top and heated by bedrock from below, is considered by Cheng, Yeung & Lau (1975). The effects of thermal conditions at the caprock, the geometry of the

reservoir, the variation of Rayleigh number, the size of the heating surface, and the dike intrusion on fluid flow and heat transfer characteristics in the reservoir are examined. The numerical results show: (1) As a result of geothermal heating, cold seawater will move inland from the ocean in the lower portion of the aquifer; rise up as a thermal plume after sufficient heat is absorbed; spread around under the caprock and finally discharge to the ocean in the upper portion of the aquifer. This open streamline convective pattern always exists in an island aquifer. (2) If the heating surface is sufficiently large, multiple closed-streamline convective cells will also be generated in the interior portion of the aquifer. These recycling convective cells prevent the complete mixing of cold water from the coast and the warmer water in the interior. (3) The number of these closed-streamline convective cells depends not only on the size of the heating surface but also the manner in which it is heated, i.e., whether it is heated by bedrock from below or the dike complex on the side. (4) Away from the thermal plumes, vertical temperature profiles exhibit a temperature reversal similar to that measured by Keller (1974). (5) The heat transfer rate on the bottom heating surface is independent of the thermal boundary condition at the caprock. (6) The temperature gradient is large in the fluid adjacent to the heating surface and in the thermal plume; this boundary layer behavior is very pronounced at large Rayleigh number.

A perturbation analysis was made for steady free convection in an island geothermal reservoir unconfined from the top (Cheng E Lau 1974; Lau E Cheng 1975). The analysis is applicable for aquifers with low Rayleigh numbers (i.e., aquifers at low temperature or with low permeability) where heat conduction is predominant. The effect of geothermal heating on the upwelling of water table is shown. To investigate the upwelling of water table at high Rayleigh numbers, numerical methods must be used for the solutions of the governing non-linear partial differential equations with non-linear boundary conditions. This phase of the work is currently underway.

Withdrawal and Reinjection of Fluids in Island Geothermal Reservoirs.

The problem of withdrawal of fluids is investigated by Cheng E Lau (1975) and Cheng E Teckchandani (1975). It is found that (1) the withdrawal rate is linearly proportional to the withdrawal pressure; (2) a symmetric location of withdrawal sites with respect to heat source will enhance the convective heat transfer from the bottom heating surface and thus prolong the lifespan of a geothermal well; (3) as a result of withdrawal of fluid, the temperature above the sink will decrease while the temperature distribution below the sink is less affected; and (4) the temperature of withdrawal fluid is relatively unaffected by the withdrawal rate. The reasons for (3) and (4) can be explained as follows: As a result of withdrawal of fluid, the flow field below the sink will experience a favorable pressure gradient, thus aiding the upward movement of the convecting flow, which in turn enhances the convective transfer on the bottom hot surface. On the other hand, the flow field above the sink will experience an adverse pressure gradient which will retard the upward movement of the hot fluid or, in some cases, reverse the direction of the convecting flow if the withdrawal pressure is large.

The problem of reinjection of fluid is studied by Cheng & Yeung (1975) and Cheng & Teckchandani (1975). If the injected fluid is colder than the surrounding fluid, a cold region is created above the injection point. For a fixed reinjection rate, the injection pressure decreases as Rayleigh number is increased. In other words, less injection pressure is needed for an aquifer at high temperature or with high permeability. For a fixed Rayleigh number, the injection rate is linearly proportional to the injection pressure.

Analytical Studies on Heat and Mass Transfer in Liquid-Dominated Geothermal Reservoirs

From the numerical solutions for free convection in 'geothermal reservoirs by Cheng, Yeung & Lau (1975), it is observed that boundary layer behavior is pronounced for flow near the heating surface and in the thermal plume at large Rayleigh numbers. Thus the boundary layer approximations analogous to the classical viscous flow theory can be applied. With these approximations, analytical solutions have been obtained for the following problems.

Steady Free Convection About Vertical Intruded Bodies. Within the framework of boundary layer approximations, similarity solutions are obtained for free convection about a vertical hot dike with surface temperature being a power function of distance from the origin; i.e., $T_w = T_\infty + Ax^\lambda$ where T_w and T_∞ are the wall temperature and the temperature of the surrounding fluid away from the dike. For the special case of an isothermal dike ($\lambda = 0$) with a height L and a width s , the local boundary layer thickness $\delta(x)$, and the total surface heat transfer rate Q are given by (Cheng & Minkowycz 1975)

$$\delta(x) = 6.3 \left[\frac{\mu \alpha x}{\rho_\infty g \beta K (T_w - T_\infty)} \right]^{1/2}, \quad (1)$$

$$Q = 0.88 S k (T_w - T_\infty)^{3/2} \left[\frac{\rho_\infty k \beta g L}{\mu \alpha} \right]^{1/2}, \quad (2)$$

where ρ , μ , and β are the density, viscosity, and the thermal expansion coefficient of the fluid, K is the permeability of the saturated porous medium, $\alpha = k / (\rho C)_f$ is the equivalent thermal diffusivity where k denotes the thermal conductivity of the saturated rock and $(\rho C)_f$ the product of the density and specific heat of the fluid.

Approximate analytical solutions for free convection about a vertical cylindrical intrusive are also obtained (Minkowycz & Cheng 1975). It is found that the ratio of total heat transfer rate for a cylinder to that for a flat plate depends only on the dimensionless parameter

ξ_L where $\xi_L \equiv \frac{2}{r_0} \left[\frac{\mu\alpha L}{K\rho_\infty\beta g(T_w - T_\infty)} \right]^{1/2}$ with r_0 denoting the radius of the cylinder. The ratio varies between 1 to 3 when ξ_L varies between 0 and 10.

Buoyancy induced Flows Adjacent to Heated impermeable Horizontal Surfaces. Similarity solutions for free convection above a heated horizontal impermeable surface with a power law variation of wall temperature are also obtained by Cheng & Chang (1975). The local thermal boundary layer thickness $\delta_T(x)$ and the total surface heat transfer rate for a horizontal heating surface with a length L and a width S are:

$$\delta_T(x) = C_1 \left[\frac{\mu\alpha x}{\rho_\infty g \beta K (T_w - T_\infty)} \right]^{2/3}, \quad (3)$$

and

$$Q = C_2 S k (T_w - T_\infty) \left[\frac{\rho_\infty K \beta L^3}{\mu\alpha} \right]^{1/3}, \quad (4)$$

where the values of C_1 and C_2 depend on the values of λ and are tabulated in Table 1.

To gain some feeling of the order of magnitude of various physical quantities given by Eqs. (1-4), computations are carried out for a heating surface of 1 km by 1 km at a temperature of 300°C embedded in an aquifer at 15°C. The physical properties used for the computations are $\beta = 3.2 \times 10^{-4}/^\circ\text{C}$, $\rho_\infty = 0.92 \times 10^6 \text{ g/m}^3$, $C = 1 \text{ cal/g-}^\circ\text{C}$, $\mu = 0.18 \text{ g/sec-m}$, $k = 0.58 \text{ cal/sec-}^\circ\text{C-m}$, and $K = 10^{-12} \text{ m}^2$. With these values, the boundary layer thickness along a dike increases from zero at the origin to 70 m at 1 km; the total heat transfer rate is 75 MW. For a horizontal heating surface of the same size, the boundary layer thickness increases from zero at the origin to 200 m at 1 km with a total heat transfer rate equal to 20 MW.

Table 1 VALUES OF C_1 AND C_2 FOR EQS. (3) & (4)

λ	C_1	C_2
0.5	4.9	1.23
1.0	4.4	1.32
1.5	4.0	1.45
2.0	3.6	1.57

Buoyancy Plumes Above a Horizontal Line Source. Similarity solutions for plume rise above a horizontal line source in a saline aquifer have been obtained by Cheng (1975). The **problem** is an extension of the work by Wooding (1963). The spreading of the buoyancy plume or the boundary layer thickness of the plume is given by

$$\delta = \frac{7.2 x^{2/3}}{\left[\frac{K \beta g Q}{\alpha^2 \mu C} \right]^{1/3}}, \quad (5)$$

where Q is the rate of heat generated per unit length of the line source. Eq. (5) shows that the spreading of the plume increases as $x^{2/3}$, and decreases as K or Q are increased. Using the previous physical properties and with Q = 20 kw, the plume spreading is about 120 m at 1 km above the point source.

Future Work

Continuous effort will be devoted to the numerical solutions of free convection in unconfined geothermal island aquifers with recharge from the ocean and rainfall. The interaction of production and withdrawal wells will also be examined. The effects of non-local thermodynamic equilibrium, the layer structure of the rock formation, and the irregular boundary of the reservoir will also be studied. Boundary layer analysis is being pursued for other problems of free and forced convection in geothermal reservoirs.

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RESEARCH ON NUMERICAL MODELING OF LIQUID GEOTHERMAL SYSTEMS

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We have developed a numerical code, called SCHAFF, which can treat problems involving slightly compressible fluid and heat transfer in multi-dimensional porous media. Solutions to the appropriate partial differential equations are obtained by the integrated finite difference method which is essentially equivalent to making mass and energy balances over finite sub-regions or elements. The resultant system of finite difference equations is solved by an iterative procedure and solutions to the fluid flow and energy equations are coupled by interlacing in time so that the temperature and velocity fields are interdependent. The useful concepts of fluid and thermal time constants as indicators of nodal response times and numerical stability limits are an inherent part of the numerical scheme.

In applying the numerical model to the problem of circulatory convection in saturated porous media, we have discussed the relevant aspects as they pertain to geothermal systems and show in Fig. 1 that results from SCHAFF on the relationship between the Rayleigh number and the dimensionless heat transfer coefficient or Nusselt number are in good agreement with numerical and experimental results from other authors. We then used the numerical model to extend these results to include the effects of temperature dependent parameters and density variations with pressure. Variations in fluid viscosity and thermal expansivity with temperature result in substantial differences in the values of the critical Rayleigh number for the onset of convection and the Rayleigh number-Nusselt number relationship compared with corresponding constant parameters results (Fig. 2). However, consideration of fluid density as a function of pressure produced no noticeable effect on convective motion.

Numerical simulations of more realistic models for circulatory convection show that for laterally bounded reservoirs, conduction of heat across the vertical sidewalls results in significant lowering of the rate of vertical heat transfer through the reservoir. For a laterally extensive reservoir, consideration of impermeable or less permeable layers above and below the convecting layer removes the restrictive assumption of constant temperatures boundaries on the permeable layer and has the effect of lowering the value of the critical Rayleigh number Ra_c while retarding convective heat transfer at values of Ra above Ra_c . The isotherm pattern for $Ra = 100$ is shown in Fig. 3.

Heat and mass transfer associated with hot spring systems was analyzed to determine the amount of heat lost by conduction to the rocks surrounding the spring conduit. As isolated cylindrical conduit model and a fault plane conduit model were considered, and the temperature drop in

the hot spring water between the source reservoir and the surface due to the conductive heat loss as determined numerically as a function of flow rate is shown in Fig. 4. The steady state temperature distribution for the case where the rock surrounding the spring is impermeable (Fig. 5) shows that heat loss from the spring distorts the normally horizontal position of the isotherms out to distances comparable to the depth of the spring conduit. Conductive heat flux at the land surface is high near the spring but near the normal or background level beyond one conduit depth. Using a radiation boundary condition at the land surface as in Fig. 5 produces a more realistic surficial temperature distribution than a constant temperature boundary condition. The time required for the conductive thermal regime to equilibrate following the development of hot spring activity can be approximated by the expression $L^2 \overline{\rho c} / 2K_m$ where L is the depth to the source reservoir. For unconsolidated sediments with low thermal conductivity, the equilibration time is about 50,000 years for a reservoir at 1 km.

The effects of fluid circulation in the rock surrounding the spring conduit were examined for systems in which the equivalent Rayleigh number (in the absence of hot spring activity) was both above and below the critical value of $4\pi^2$. With $Ra < 4\pi^2$, circulatory convection is set up due to the presence of the hot spring, but causes only slight effects on the thermal regime in the rock surrounding the spring conduit and on the conductive heat loss and temperature drop associated with the spring. For the case with $Ra > 4\pi^2$, circulatory convection resulting from the temperature difference $T_b - T_s$ between the source reservoir and the land surface dominates the thermal and hydrologic regimes and significantly reduces the conductive heat loss and temperature drop for the spring.

The results of this investigation demonstrate the usefulness of numerical modelling to describe the natural conditions of heat transfer and fluid flow in geothermal areas. Given preliminary thermal, hydrologic, and geochemical information, this technique can be used effectively as a guide to further data collection in undeveloped areas. As sufficient parametric and geometric information is obtained to allow simulation of the natural systems, the numerical model can be used to evaluate methods for energy development. In particular, studies are being planned of energy development under conditions of fluid reinjection which can maintain the reservoir fluid in a liquid state and possibly result in the recovery of significant fractions of stored heat. Numerical studies of the feasibility of storing and recovering waste thermal water from power plant operations in cold water aquifers are also anticipated. In addition, a modification of the **SCHAFF** program to include stress-strain behavior of porous media is currently being tested for simulation of land subsidence associated with geothermal reservoir development.

Further work on the calculational model is also planned. Incorporation of a suitable scheme for treating anisotropy and associated tensorial quantities such as permeability and thermal dispersivity would extend the range of the problems which could be analyzed with **SGHAFF**. It would also be desirable to include a general mesh-generating routine and a graphics capability for fluid velocity vector plotting.

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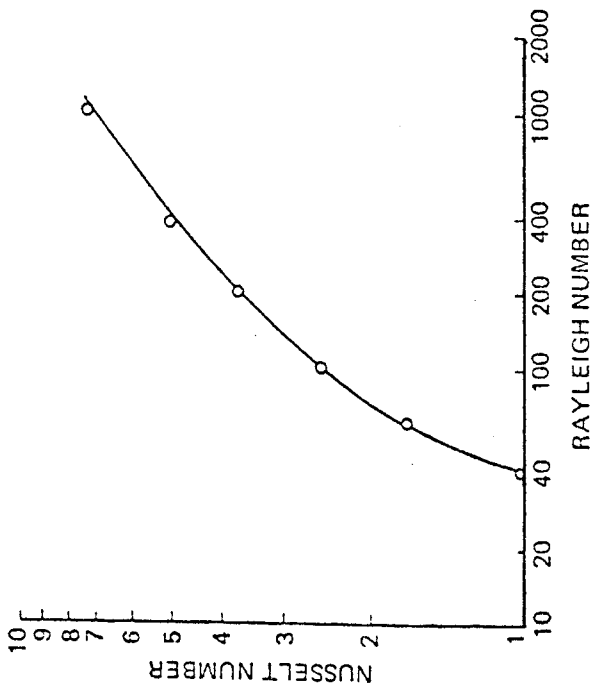


Figure 1 Rayleigh number versus Nusselt number for fluid convection in an extensive horizontal layer with constant fluid properties. Solid line based on SCHAFF result, open circles from numerical and experimental results by Combarrous and Boles (1973).

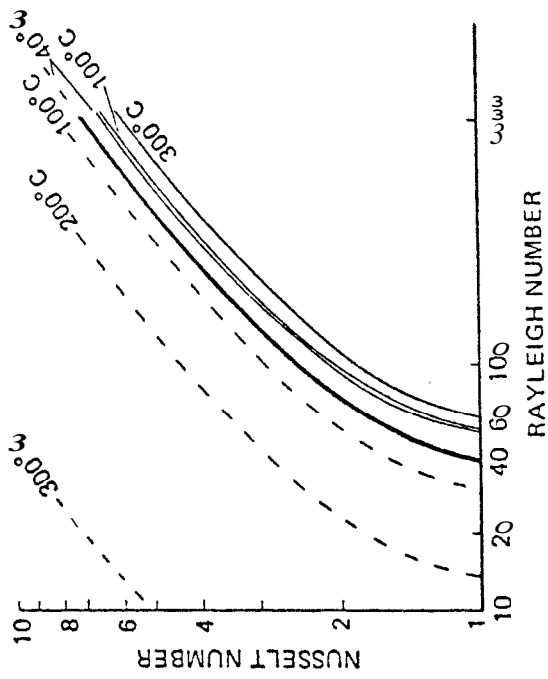


Figure 2. Results from SCHAFF for circulatory convection in an extensive horizontal layer with temperature-dependent fluid properties. Dashed curves for Ra evaluated at cold-side temperature T_0 ; solid curves for Ra evaluated at mean temperature $(T_1 + T_0/2)$. Heavy solid curve for constant fluid properties.

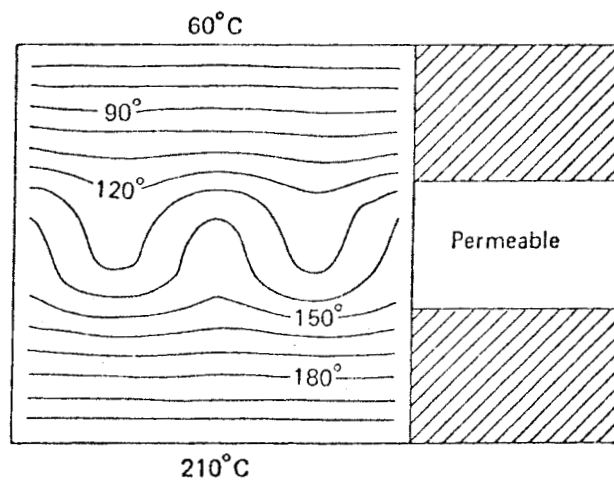


Figure 3. isotherms for 3-layer cellular convection model with $Ra = 100$.

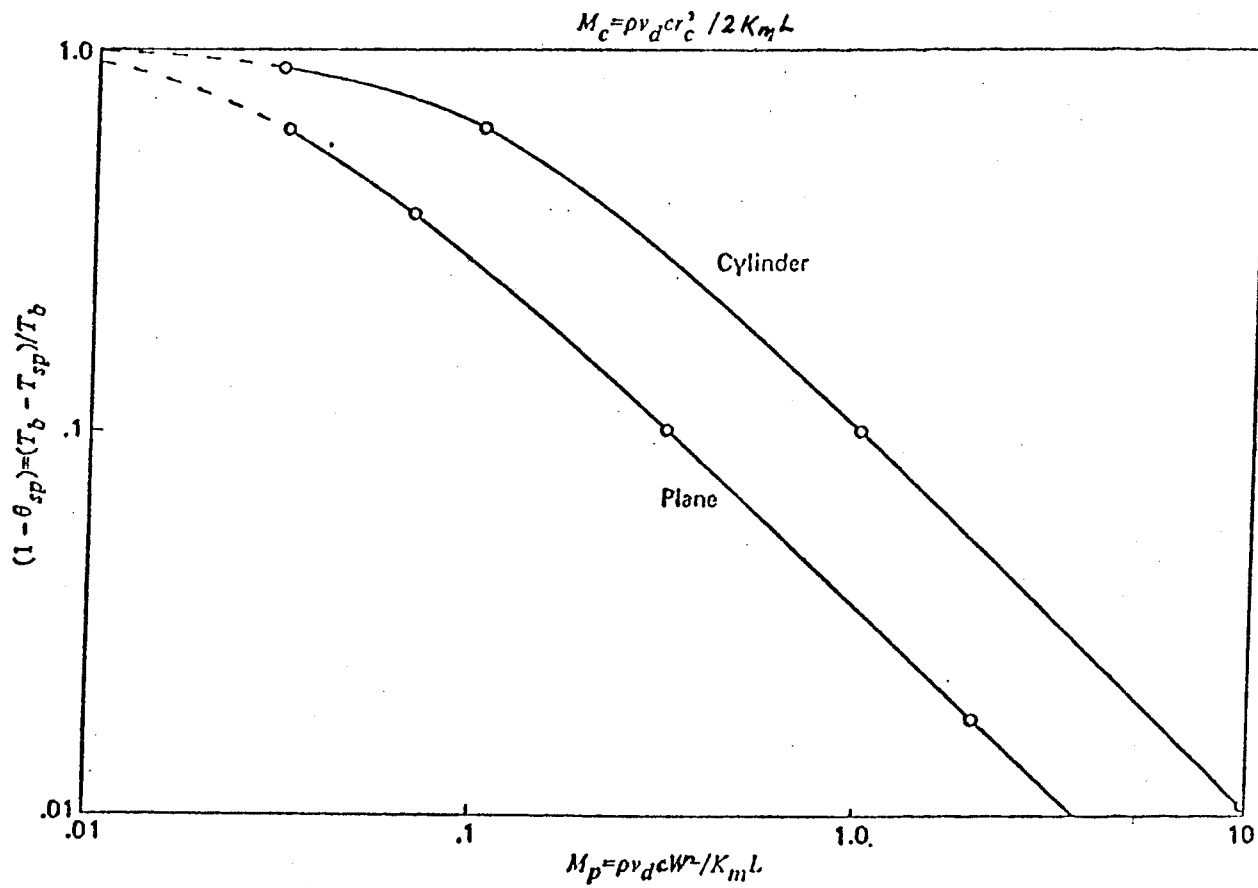
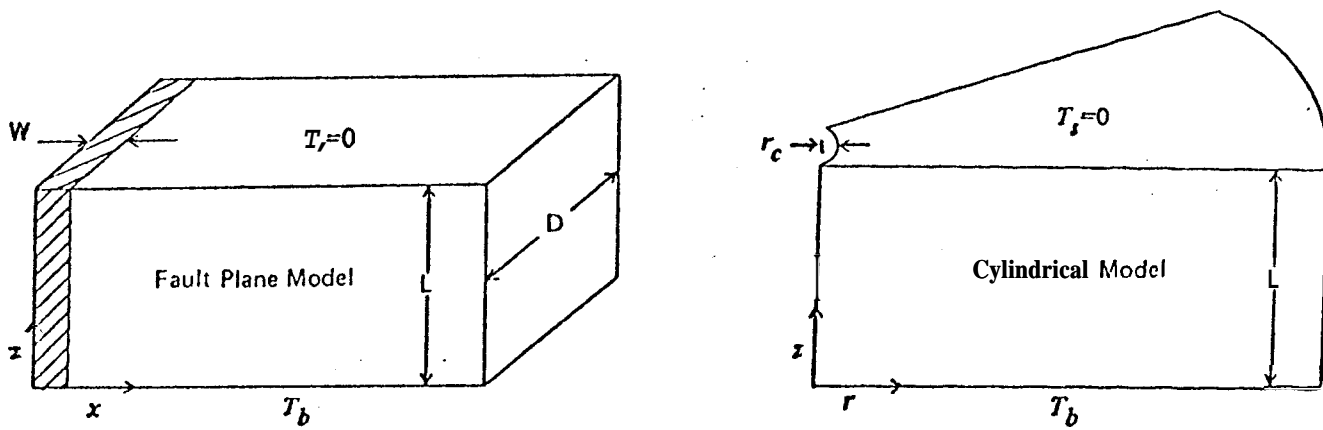


Figure 4. Relationships between dimensionless flow rates (M_c, M_p) and dimensionless temperature drop ($1 - \theta_{sp}$) due to conductive heat loss in cylindrical and fault plane hot spring models.

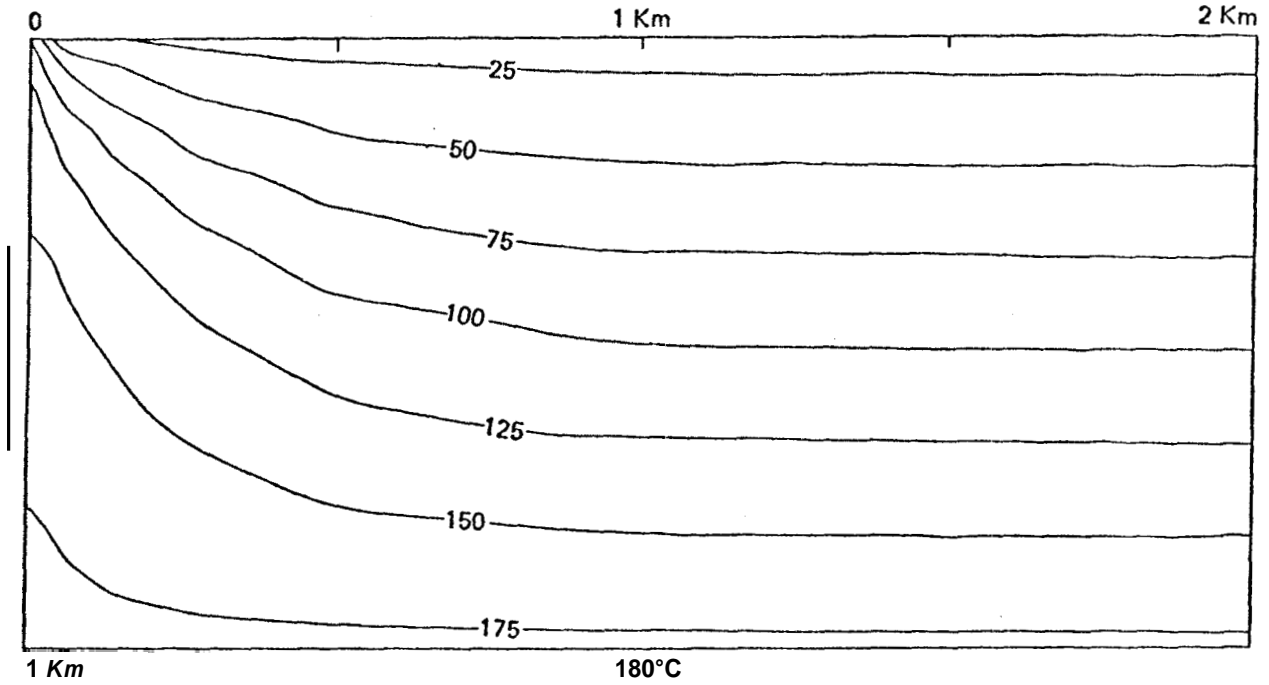


Figure 5. Steady state temperature distribution in fault plane hot spring model with discharge = 10^5 Kg/d, $W = 10\text{m}$, $D = 1\text{ Km}$, and $Ra = 0$ ($k = 0$), and $H = 10^{-6}$ cal/sec $^{\circ}\text{C}$ $-\text{cm}^2$ at land surface.

FINITE ELEMENT SOLUTION OF GEOTHERMAL ENERGY EXTRACTION

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The objective of this theoretical work is to simulate numerically the following two basic problems in the area of geothermal energy extraction: (1) initiation and extension of fracture in hot dry rocks by hydraulic fracture; and (2) circulation of water through the fractured zone and back up to the ground surface. In addition, it has become evident that the following third problem area also requires careful consideration: (3) the study of thermally induced secondary cracks and their effects on power production. The basic method of approach involves a finite-element numerical simulation coupled with some analytical computations.

Basic Equations

The basic field equations for the water flow and heat transfer in a crack have been formulated for one- and two-dimensional cases. These equations include (a) crack width varying arbitrarily in time and space; (b) heat convection due to flow of water, heat conduction in water, and heat supply by conduction from the rock; (c) an accurate mathematical model for the thermodynamic properties of water (according to 1968 ASME Steam Tables), i.e., the pressure-density-temperature relationship (with the dependence of compressibility, thermal expansion coefficient and heat capacity on pressure and temperature). The basic differential equations have been obtained by applying the conditions of conservation of mass, of linear momentum, and of energy to the cross-section of crack, using an assumed velocity profile. In the case of unidirectional flow, for example, these equations are:

$$\text{mass; } \frac{\partial}{\partial t} (\rho w) + \frac{\partial q}{\partial x} = 0 ; \quad (1)$$

$$\text{momentum; } \frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha \frac{q^2}{\rho w} \right) = -w \frac{\partial p}{\partial x} - 2\tau + \rho w g_x + \frac{4}{3} \mu \frac{\partial}{\partial x} \left(\frac{q}{\rho} \right) \quad (2)$$

$$\begin{aligned} \text{energy; } \rho w C_w \frac{\partial T}{\partial t} + C_w q \frac{\partial T}{\partial x} + \left\{ \frac{3}{2} (\beta - \alpha) \left(\frac{q}{\rho w} \right)^2 \frac{\partial q}{\partial x} + (\alpha - 1) \frac{q}{\rho w} \frac{\partial q}{\partial t} \right. \\ \left. - (\beta - \alpha) \left(\frac{q}{\rho w} \right)^3 \frac{\partial (\rho w)}{\partial x} \right\} = \left\{ \frac{2u}{3} \left[\frac{\partial^2}{\partial x^2} \left(\alpha \frac{q^2}{\rho w} \right) - \frac{2q}{\rho w} \frac{\partial^2}{\partial x^2} \left(\frac{q}{\rho} \right) \right] \right\} \\ + 2\tau \frac{q}{\rho} + \frac{\partial}{\partial x} \left(k w \frac{\partial T}{\partial x} \right) + 2h(T_r - T) ; \quad (3) \end{aligned}$$

$$\text{equation of state for water; } p = f(\rho, T) ; \quad (4)$$

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where ρ is the mass density; q is the mass flux across the width of the crack; p is the pressure; τ is the shear force at the interface between fluid and rock; g_x is the average body force on the fluid; C_w , k , and h define the heat capacity, heat conductivity within the fluid, and heat conductivity between fluid and rock, respectively; T and T_r are the fluid's and the rock's temperature, respectively. The equation of state for water in the range of pressure and temperature relevant to the geothermal problem is given in the 1968 ASME steam tables. This equation is used in the numerical calculations.

The parameters α and β , as well as the shear force τ , in Eqs. (2) and (3) depend on the geometry of the velocity profile across the crack width. For a parabolic profile, for example, one has $\alpha = 1.2$, $\beta \approx 1.54$ and $\tau = \frac{6\mu q}{2\rho w}$, where μ is the fluid viscosity. However, in the operation stage, the fluid velocity can be high and a turbulent flow with an almost uniform profile of mean velocity may be a more appropriate assumption.

Finite Element Formulation for the Fluid

To obtain the corresponding finite-element equations, linear spatial variation for pressure, temperature, and mass flow within each element is assumed. Then a systematic application of Galerkin's method gives the basic finite-element equations for the fluid flow. For the unidirectional flow, for example, these equations are

$$\tilde{K}_1 \dot{\tilde{p}} + \tilde{K}_2 \dot{\tilde{T}} + \tilde{K}_3 \tilde{p} + \tilde{f} = \tilde{0}, \quad (5)$$

$$\tilde{K}_4 \dot{\tilde{T}} + \tilde{K}_5 \tilde{p} + \tilde{K}_6 \tilde{T} + \tilde{g} = \tilde{0}, \quad (6)$$

$$\tilde{C} \tilde{q} + \tilde{K}_1 \dot{\tilde{p}} + \tilde{K}_2 \dot{\tilde{T}} + \tilde{f}^{(0)} = \tilde{0}. \quad (7)$$

In these equations superimposed dot denotes the partial time derivative; \tilde{p} , \tilde{T} , and \tilde{q} denote pressure, temperature, and mass flow at the two nodes of each element; and the coefficient matrices, as well as the corresponding forcing functions, are either constant or nonlinear functions of \tilde{p} , w , and \tilde{q} , as well as linear function of \tilde{p} , w , and \tilde{q} .

Equations (5) - (7) together with the equation of state for water, Eq. (4) are sufficient for the calculation of the fluid flow, provided that the crack width is known at all nodal points. For an assumed crack width (obtained in a previous time step) these equations are solved for \tilde{p} , \tilde{q} , \tilde{p} , and \tilde{T} is time steps with iteration at each step, until the maximum change of each quantity with respect to the previous value is less than a prescribed limit; see, however, the following discussion.

Combination of Finite Element Model with Analytical Solutions

Test runs of the finite element program for the solid in combination with the finite element program for the flow in the crack have indicated that the requirements for computer time are extremely high and convergence very slow. The extension jumps of the crack in the finite element grid must be very small, or else enormous spurious changes of pressure in the fluid are obtained. Dense spacing of the nodes in turn requires very short time steps, in order to avoid numerical instabilities. However, the response of the elastic rock due to pressure in the crack as well as cooling from the crack can be quite accurately described by analytical formulas, and this allows reduction of computer time as well as higher accuracy of numerical calculations. It is therefore concluded that the following numerical approach is most effective:

(a) In case of hydraulic fracturing, the pressure in water in excess of hydrostatic remains essentially uniformly distributed at a 1 times and water temperature is equal to that of the adjacent rock. In this case, the finite-element program for the solid alone may be used treating the fluid pressure as the input;

(b) In case of operation stage, the finite-element program for the fluid flow and the heat transfer in the fluid may be used in conjunction with analytical solutions for the elastic solid (rock) and the heat conduction in the rock (using the concept of cooling penetration depth and the heat transfer coefficient)..

Finite Element Formulation for the Solid (Rock)

For analyzing the fracture of the solid (rock), a two-dimensional finite element program with a water-filled crack has been written. The criterion for the propagation of the crack can be formulated in this program either by means of a stress-intensity factor, or by means of a strength (limiting stress value in the finite element). The former type of strength criterion is usually more appropriate, provided the rock is relatively homogeneous and flawless and the crack is sufficiently large. Among the various methods of evaluating the stress intensity factor in the finite element analysis, the method of calibrated crack-tip element of ordinary type has been chosen as the most efficient one. This program must be subjected to more testing, and the method by which the boundary conditions representing the surrounding infinite solid can be best simulated, must be identified.

Examples and Estimates

In order to develop an understanding for the various physical processes which are involved in this general area, some simple analytical results have been developed. In the following, these results are briefly discussed.

Crack Extension: The extension of a crack in a rock mass as a function of the total mass flow can be estimated in the following manner. If the maximum crack opening is A and the crack radius is R , then for an elliptical opening the total fluid volume in the crack is given by $\frac{4}{3}\pi\Delta R^2$.

On the other hand, according to the Griffith criterion, one has $p - S = AR^{-\frac{1}{2}}$

and $A = 8(p-S)R$ where $A = \frac{\pi E \gamma}{2(1-\nu^2)}$, S is the tectonic stress normal to the

face of the crack, $B = \frac{4(1-\nu^2)}{\pi E}$, γ is the surface energy, E is the elastic

modulus of the rock, and ν is the corresponding Poisson's ratio. If $M = \rho V$ is the total mass of the fluid in the crack, one then obtains

$$R = R_o \left(\frac{M}{M_o} \right)^{2/5}, \quad (8)$$

$$p - S = (p_o - S) \left(\frac{M}{M_o} \right)^{-1/5}, \quad (9)$$

where subscript o refers to the initial values. For example, if the fluid is pumped in at a constant rate q , one has $M = M_o + qt$, and Eqs. (8) and (9) give the crack radius and the corresponding pressure as functions of time; the latter is illustrated in Fig. 1. Except for the transient effects, it is seen that $(p-S)$ remains relatively constant as the crack grows.

Heat Extraction: For the heat extraction in a steady-state operation the following equation estimates the temperature of the fluid along a "stream tube" (see Figs. 2 and 3):

$$T_w = T_r^{in} - \left\{ \left[T_r^{in} - T_w^{in} + \left(T_r^{in} - T_r^o \right) / \alpha l_o \right] e^{-\alpha x} + \left(T_r^{in} - T_r^o \right) \left(\frac{x}{l_o} - \frac{1}{\alpha l_o} \right) \right\}, \quad (10)$$

where

T_w = water temperature

T_r = rock temperature

a = length of the stream tube

$a = 2\bar{h}/C_w q$

q = mass flow per unit length measured normal to the stream tube

C_w = water heat capacity,

and where "in" denotes the "inlet" and "o" denotes the outlet values. Here \bar{h} is given by

$$\bar{h} \approx \sqrt{\frac{\rho_r k_r C_r}{12t}}, \quad (11)$$

where

ρ_r = rock's mass-density

k_r = rock's heat conductivity

C_r = rock's heat capacity

t = time

Fig. 2 shows the result obtained from (10) for a case in which $\lambda_o = 1200\text{m}$, $T_r^{\text{in}} = 300^\circ\text{C}$, $T_r^{\text{o}} = 240^\circ\text{C}$, $T_w^{\text{in}} = 65^\circ\text{C}$, and $q = 0.2 \text{ kg/m sec}$. These results check very accurately with the numerical results. This is shown in Fig. 3 where the results of the finite-element solution of the complete set of equations are shown by solid lines.

It should be noted that the thermal boundary layer in the rock, in which a thermal gradient exists, is very small when compared with the length of the **crack**. This requires that the numerical calculations be coupled with some analytical estimates.

The example of Figs. 2 and 3 does not include the secondary cracking due to the very large thermal stresses which may develop as the rock is cooled. Both analytical and numerical calculations have shown that these secondary cracks are very likely to develop and change the nature of the heat flow as well as that of the fluid flow. These and other related problems are now being studied.

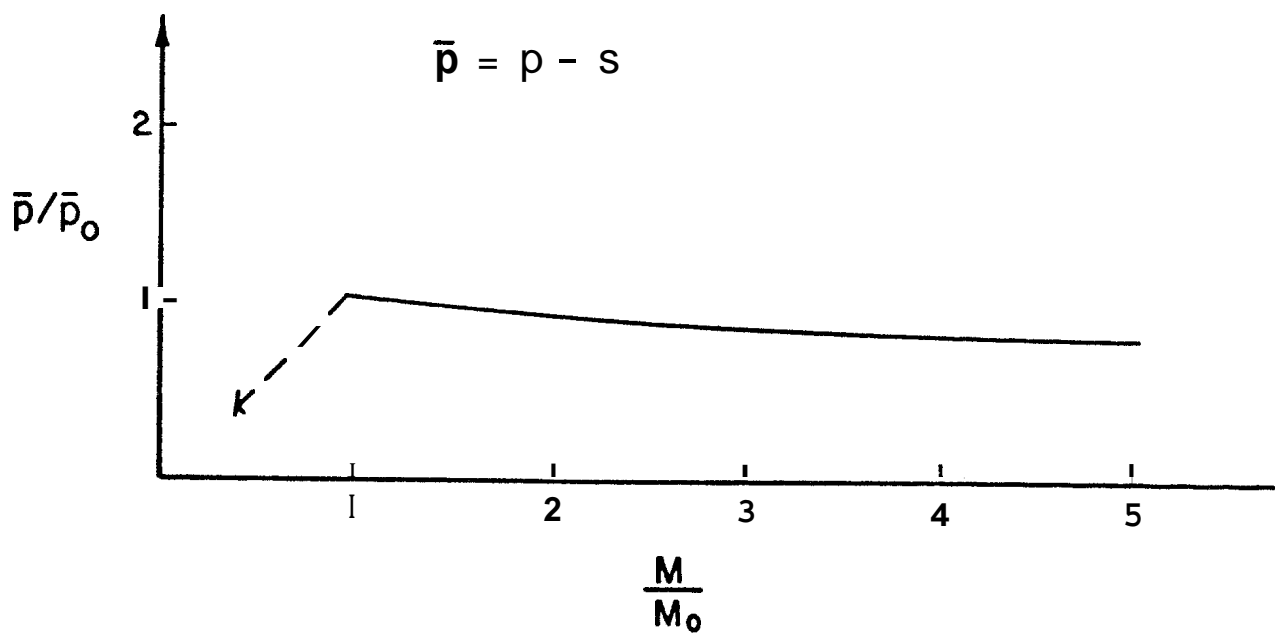


Figure 1

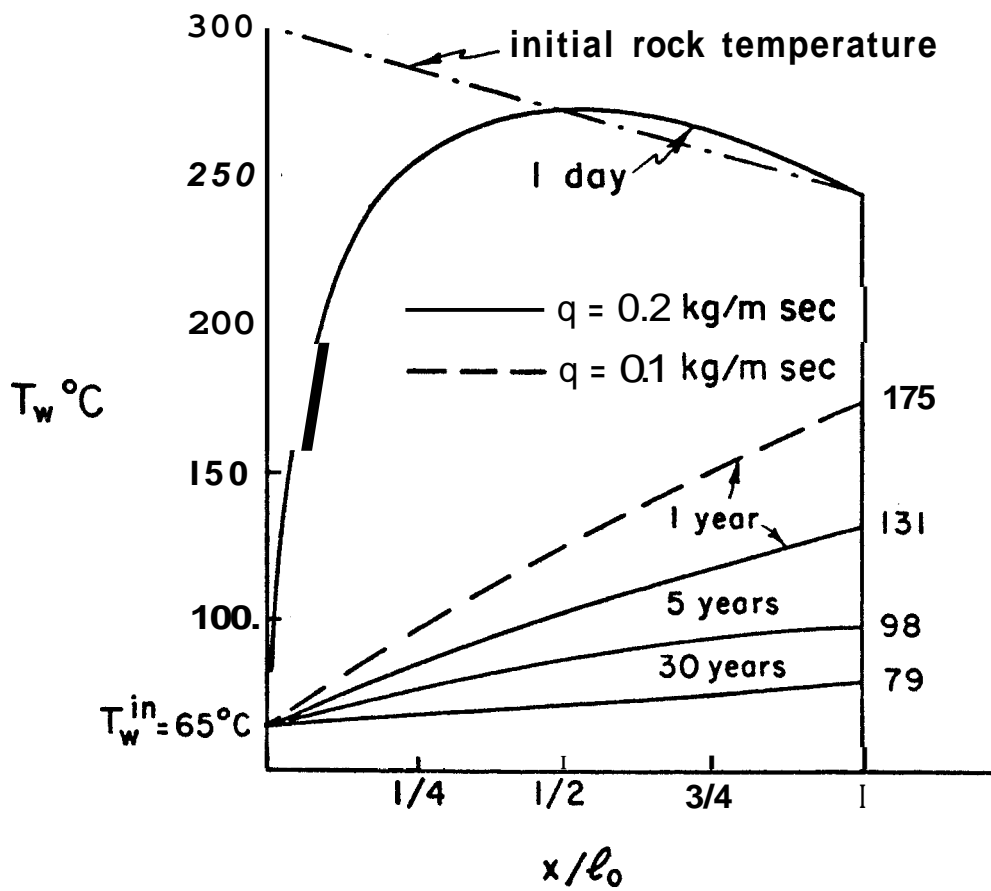
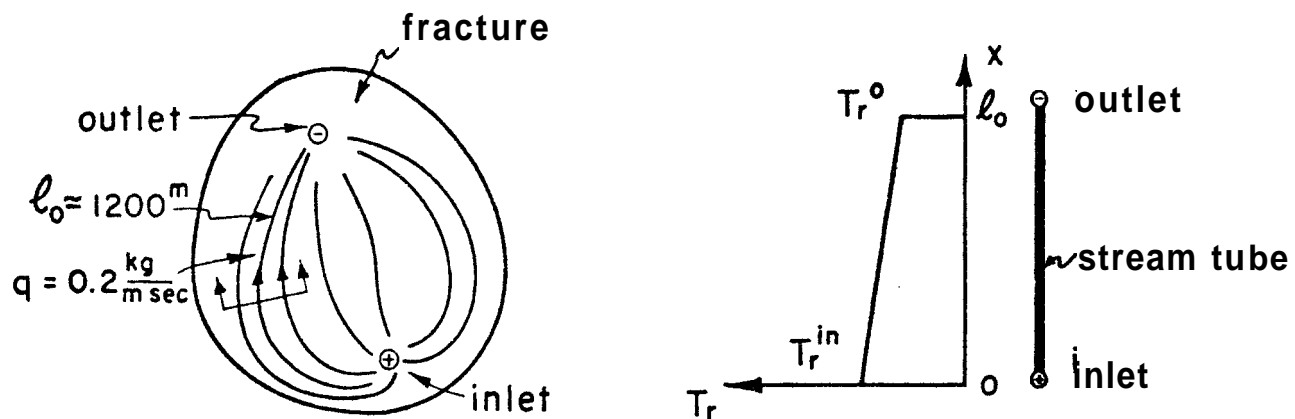


Figure 2

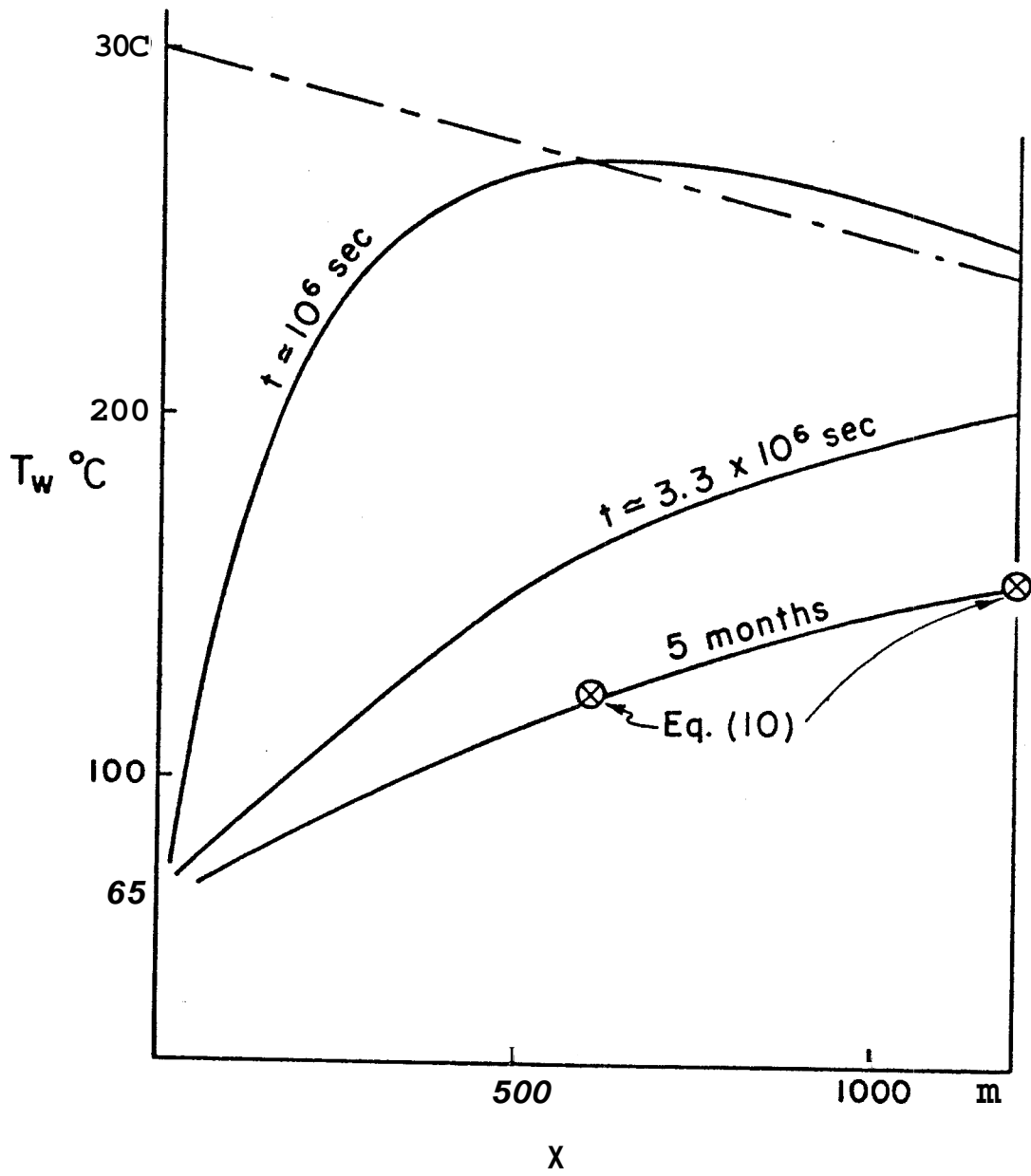


Figure 3

NUMERICAL MODELING OF HYDROTHERMAL REACTIONS
IN GEOTHERMAL RESERVOIRS

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Although the corrosion and scaling problems associated with handling geothermal fluids are well known, the effects of hydrothermal reactions are often overlooked in geothermal reservoir modeling. Water-rock chemistry can be expected to affect the evolution of a reservoir in at least three ways: (a) the thermodynamic properties of water are affected by the dissolved solids - this is especially important in two-phase regimes, (b) the porosity and permeability change with time due to dissolving and precipitation as well as due to the volume change associated with alteration, and (c) the heats of reaction may contribute directly to the energy production.

Table 1 summarizes the important hydrothermal reactions in a granitic source rock together with the heats of reaction and associated volume changes. Note that the available chemical energy is comparable to the thermal energy while the associated volume changes are an order of magnitude larger than those due to thermal contraction.

Although significant chemical energy exists, it cannot always be extracted. One of the first questions we addressed was the delineation of reservoir conditions under which one could expect to extract significant chemical heat. For the case of dissolving-precipitation reactions, a comparison of thermal energy with chemical energy leads to a simple relation between solubility and heat of reaction for a given ratio of chemical to thermal energy extracted. Because the rate of dissolving is controlled by the solubility at the outlet temperature, the resulting relation is independent of all crack and flow parameters. In the case of quartz, the solubility at 300°C is too low for chemical heat to make a contribution - thermal energy is extracted far faster than chemical in all cases.

In the case of alteration reactions, however, the reaction rate is not limited by solubility and, depending on the alteration rate, significant chemical energy may be extracted. We have delineated the combinations of flow parameters, crack parameters, heats of reaction and alteration rates for which chemical energy associated with the alteration may be extracted. One of the objectives of our experimental program is to determine alteration rates in typical reservoir rocks, and thus assess the importance of such reactions to the total thermal regime.

The changes in porosity and permeability associated with both dissolving and alteration reactions are easily incorporated into the standard finite difference schemes commonly used in numerical reservoir modeling. Our approach to the inclusion of such effects will be discussed.

IMPORTANT REACTIONS IN GRANITIC ROCK
(CHEMICAL REACTIONS TAKEN FROM HELGESON, 1969)

PROCESS	Heat released		Solid volume change per 100g of initial min. $\Delta V_s (\text{cm}^3/100\text{g})$
	per mole of initial min. $\Delta H (\text{kcal/mole})$	per 100g of initial min. $\Delta H (\text{kcal}/100\text{g})$	
<u>HYDROTHERMAL ALTERATION</u>			
$2\text{NaAlSi}_3\text{O}_8(\text{s}) + 2\text{H}^+ + \text{H}_2\text{O} \longrightarrow \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4(\text{s}) + 4\text{SiO}_2(\text{s}) + 2\text{Na}^+$ Low Albite \longrightarrow Kaolinite + α -quartz	11.21	4.27	-1.882
$3\text{KAlSi}_3\text{O}_{10}(\text{s}) + 2\text{H}^+ \longrightarrow \text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2(\text{s}) + 6\text{SiO}_2(\text{s}) + 2\text{K}^+$ Microcline \longrightarrow muscovite + α -quartz	2.96	1.063	-5.907
<u>DISSOLVING AND PRECIPITATION</u>			
$\text{SiO}_2(\text{s}) + 2\text{H}_2\text{O} \longrightarrow \text{H}_4\text{SiO}_4(\text{aq})$ α -quartz	-6.22	-10.352	-37.760
<u>COOLING</u>			
$\text{GRANITIC ROCK } (300^\circ\text{C}) \longrightarrow \text{GRANITIC ROCK } (65^\circ\text{C})$ $(\rho_R = 2.65 \text{ g/cm}^3, C_R = 0.25 \text{ cal/g}^\circ\text{C}, \beta_R = 2.5 \times 10^{-5} / ^\circ\text{C})$	-	5.875	-0.2217

TABLE 1.

PROGRESS REPORT ON A MATHEMATICAL MODEL OF A
PARALLELEPIPED RESERVOIR WITH NO PENETRATING
WELLBORE AND MIXED BOUNDARY CONDITIONS

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R. Celati

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and

G. Neri

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The object of this work is to develop a mathematical model, as suggested by H. J. Ramey [1], for simulating unsteady flow in geothermal reservoirs containing a single phase fluid.

The reservoir is a homogeneous, isotropic parallelepiped with no-flux or constant pressure walls, according to the most probable geological conditions.

At present our model considers a non-penetrating wellbore as it will first be applied to Travale geothermal field where many data are available for a productive well with no penetration at all.

The computer program is easily modified, however, to suit other well conditions such as partial penetration or fractured wells. The finite radius of our well was simulated computing the pressure drop at a given distance from the point sink.

A parallelepiped with no-flux walls and top, constant pressure at the bottom, was obtained from Green's instantaneous source functions VI (x), VII (y), IX (z) according to the nomenclature used in ref. [2].

The solution for constant rate q is:

$$\Delta p(M, t) = \frac{q}{\phi c x_e y_e z_e} \int_0^t \left[1 + 2 \sum_{n=1}^{\infty} e^{-\frac{n^2 \pi^2 \eta (t-\tau)}{x_e^2}} \cdot \cos \left(n \pi \frac{x_w}{x_e} \right) \cdot \cos \left(n \pi \frac{x}{x_e} \right) \right] \cdot \left[1 + 2 \sum_{n=1}^{\infty} e^{-\frac{n^2 \pi^2 \eta (t-\tau)}{y_e^2}} \cdot \cos \left(n \pi \frac{y_w}{y_e} \right) \cdot \cos \left(n \pi \frac{y}{y_e} \right) \right] \cdot \left[2 \sum_{n=1}^{\infty} e^{-\frac{(2n-1)^2 \pi^2 \eta (t-\tau)}{4 z_e^2}} \cdot \cos \left(\frac{2n-1}{2} \pi \frac{z_w}{z_e} \right) \cdot \cos \left(\frac{2n-1}{2} \pi \frac{z}{z_e} \right) \right] d\tau \quad (1)$$

If we define the dimensionless groups as follows:

$$P_0 = \frac{2\pi z_e k \Delta p}{q \mu} \quad , \quad t_{DA} = \frac{\eta t}{x_e y_e} \quad , \quad \tau_{DA} = \frac{\eta \tau}{x_e y_e} \quad (2)$$

eq. (1) gives:

$$P_D = 2\pi \int_0^{t_{DA}} \left[1 + 2 \sum_{n=1}^{\infty} e^{-n^2 \pi^2 (t_{DA} - \tau_{DA}) \frac{y_e}{x_e}} \cdot \cos\left(n\pi \frac{x_w}{x_e}\right) \cdot \cos\left(n\pi \frac{x}{x_e}\right) \right] \cdot \left[1 + 2 \sum_{n=1}^{\infty} e^{-n^2 \pi^2 (t_{DA} - \tau_{DA}) \frac{x_e}{y_e}} \cdot \cos\left(n\pi \frac{y_w}{y_e}\right) \cdot \cos\left(n\pi \frac{y}{y_e}\right) \right] \cdot \left[2 \sum_{n=1}^{\infty} e^{-(2n-1)^2 \pi^2 (t_{DA} - \tau_{DA}) \frac{x_e y_e}{4z_e^2}} \cdot \cos\left(\frac{2n-1}{2} \pi \frac{z_w}{z_e}\right) \cdot \cos\left(\frac{2n-1}{2} \pi \frac{z}{z_e}\right) \right] d\tau_{DA}$$

Substituting $t_{DA} - \tau_{DA} = \theta_{DA}$ implies:

$$d\tau_{DA} = -d\theta_{DA} \quad \text{and gives:}$$

$$P_D = 2\pi \int_0^{t_{DA}} \left[1 + 2 \sum_{n=1}^{\infty} e^{-n^2 \pi^2 \theta_{DA} \frac{y_e}{x_e}} \cdot \cos\left(n\pi \frac{x_w}{x_e}\right) \cdot \cos\left(n\pi \frac{x}{x_e}\right) \right] \cdot \left[1 + 2 \sum_{n=1}^{\infty} e^{-n^2 \pi^2 \theta_{DA} \frac{x_e}{y_e}} \cdot \cos\left(n\pi \frac{y_w}{y_e}\right) \cdot \cos\left(n\pi \frac{y}{y_e}\right) \right] \cdot \left[2 \sum_{n=1}^{\infty} e^{-(2n-1)^2 \pi^2 \theta_{DA} \frac{x_e y_e}{4z_e^2}} \cdot \cos\left(\frac{2n-1}{2} \pi \frac{z_w}{z_e}\right) \cdot \cos\left(\frac{2n-1}{2} \pi \frac{z}{z_e}\right) \right] d\theta_{DA} \quad (3)$$

We carried out summations for several values of t_{DA} along with numerical integration.

We had some computing difficulty in evaluating the series with very small values of t_{DA} as they do not rapidly converge. We tested our method by solving two-dimensional problems whose solutions were already known by the superposition in space of exponential integrals [3].

The great advantage of this method is that we can change boundary conditions simply by changing a FORTRAN subroutine. The program was first used to produce Horner graphs for comparing the theoretical and experimental plots, with a view to selecting the appropriate model.

Figures 1, 2, 3 and 4 show the Horner plots for a cube and a square parallelepiped both having a constant pressure or closed bottom. These theoretical Horner plots do not give the straight line section with slope of 1.15 found in two-dimensional models. This means that the procedure commonly used for evaluating the kh product cannot be directly applied when the hypothesis of this model are appropriate.

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NOMENCLATURE

- c = compressibility
 k = permeability
 M = point where pressure is measured
 p_D = dimensionless pressure drop
 Δp = pressure drop
 q = flow rate
 t = time
 t_{DA} = area-based dimensionless time
 x, y = horizontal coordinates
 z = vertical coordinate
 η = hydraulic diffusivity
 θ_{DA}, τ_{DA} = dimensionless variables of integration
 μ = viscosity
 τ = variable of integration
 ϕ = porosity

SUBSCRIPTS

- e = reservoir dimensions
 w = source or sink location
 $V_{II}(\mathbf{x}), V_{II}(y)$ = Basic instantaneous source functions, for an infinite plane source in an infinite slab reservoir with prescribed flux at the boundary, applied to the x and y coordinates.
 $V_X(z)$ = Basic instantaneous source function for an infinite plane source in an infinite slab reservoir with prescribed flux at $z=0$ and prescribed pressure at $z=z_e$.

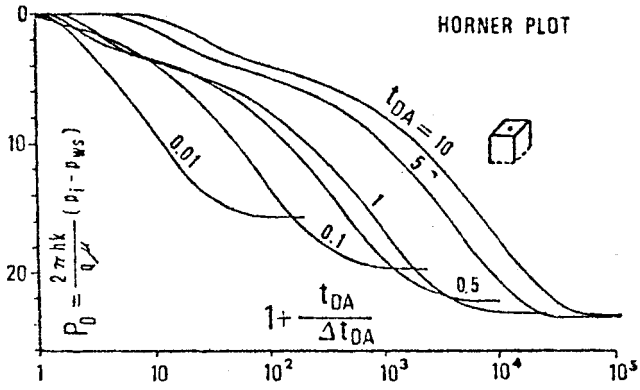


Fig.1— Closed cube with constant pressure at the bottom

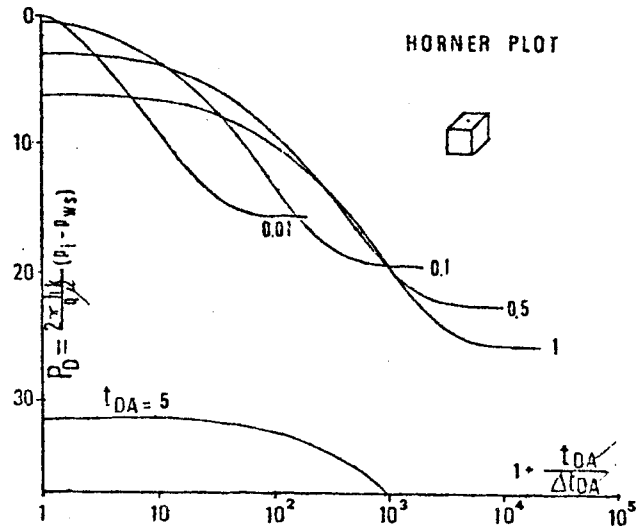


fig.2— Closed cube

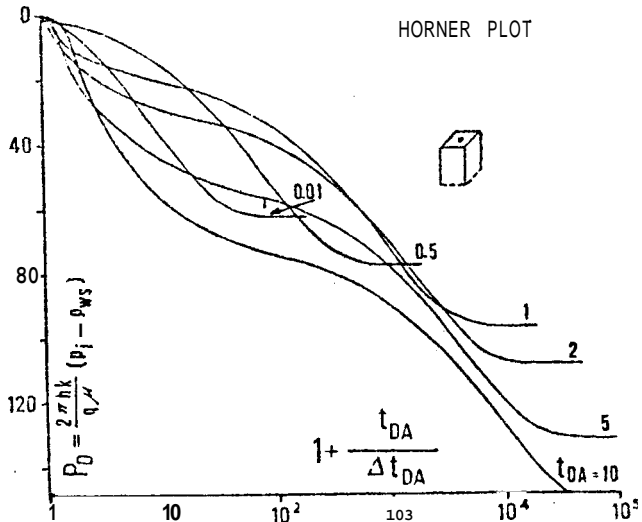


Fig.3-- Closed parallelepiped with constant pressure at the bottom

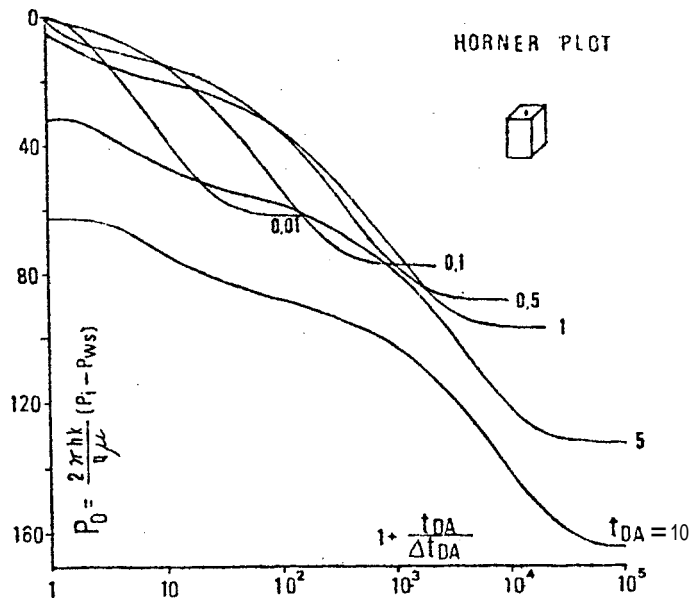


Fig.4— Closed parallelepiped

FUNDAMENTAL STUDY OF CHANGING OF PHASE IN POROUS MATERIALS

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The research program on geothermal energy developed in our laboratory for the last two years is mainly focussed on the fundamental problem of changing of phase in porous media.

In this report I would like to discuss two points: the main objectives of this program and our current activities.

Statement of the Problem

A high energy geothermal system is generally defined as an aquifer in which thermodynamic conditions, i.e., pressure and temperature, are relatively important and thus may be used to produce mechanical and electrical energy.

A number of studies have been conducted during the last ten years to understand the existence of hot temperature geothermal fields; convection is now recognized as one of the main causes.

The effect of convection is to induce an important upward head flux and therefore very high temperatures in the upper part of the reservoir.

The heat accumulation in the upper part of a geothermal field, i.e., the stored energy, is composed of two parts:

- (1) The energy stored within the solid phase. This is generally the more important aspect, and
- (2) The energy stored within the fluid phase.

Although during production only the fluid is recovered, due to changing of phase in the reservoir, heat transfer occurs between the solid matrix and the fluid phase. It is therefore evident that solid contribution to the vaporization may be considered as most important as far as the recovery of energy and the thermodynamic evolution of the reservoir are concerned.

This problem of heat transfer between the porous matrix and the fluid is particularly important in the case of a fissured medium with large block dimensions, which often occurs in geothermal fields. In that case it is unrealistic to assume an equilibrium temperature between the fluid and the matrix blocks while the fluid is flowing and changing of phase within the fissures is taking place. The best we can do is to try to define a mean heat transfer between the rocks and the fluid. If the blocks are microporous, the problem is very similar to that of heat transfer with changing of phase in a dispersed medium. This is the problem we are interested in.

Mathematical Model, Dimensionless Parameters

In a first approach, by making the following assumptions:

- a. Rigid porous media
- b. Capillary effects negligible
- c. Negligible compressibility work
- d. Steam is considered as a perfect gas
- e. Equilibrium Temperature between the fluid and the solid.

The governing equation may be written as

Mass continuity equation, heat transfer equation
and the pressure equation

Dimensional analysis from these equations leads to dimensionless qualities, taking into account the influence of

- Porosity
- Nature of porous medium
- Grain-size or pore diameter
- Initial conditions
- Boundaries conditions

This model will be tested and used to determine experimental correlations by using the data obtained on an experimental model which is described next.

Experimental Model

This model is one dimensional with a circular section of 5 cm diameter and a length of two meters. To avoid perturbing influences in the production section it is constituted of two symmetrical parts so the temperature gradient in this section is equal to 0 and then no end effects can modify the steam quality.

The porous media is set inside an insulating envelope and an outside metal cylinder maintains the pressure and ensures controlled heating.

The fluid is injected into the porous media and maintained under pressure, saturation (gamma ray absorption), mass balance and steam quality (condenser).

By using these results and having defined the heat transfer from envelope to the porous media (this parameter takes an important place in the energy balance), we will determine (1) the porous material contribution to the vaporization, and (2) the possibilities of testing the mathematical model.

The experimental mode is now almost finished and a simple numerical model has been established to estimate the heat transfer from the envelope to the porous media.

We have obtained a qualitative simulation of the effect, in the example where saturation is uniformly varying in the porous media.

THERMAL DEPLETION OF LIQUID-DOMINATED GEOHERMAL RESERVOIRS WITH FRACTURE AND PORE PERMEABILITY

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The lifetime of a geothermal power plant is strongly dependent on the fracture spacing and fracture permeability of the geothermal reservoir. This conclusion is based on a solution of three coupled linear rate equations for the time dependence of the average temperature of the rock, pore fluid and fracture fluid. By averaging temperature over the entire reservoir and assuming all the fluid is reinjected, effects such as drawdown are ignored, and an upper bound for the reservoir heat content and average wellbore temperature is determined as a function of time. Heat transfer from the rock to the fluid by conduction both in fractures and in pores and by the flow of fluid through the pores is accounted for in this model.

Several approaches to the problem of thermal depletion of a geothermal reservoir are possible. A volumetric estimate of heat in place may be based on an estimate of the volume of fluid available (Towse, 1975). Heat obtained from the rock may be estimated and included in the thermal resource estimate. An estimate for the resource lifetime is then made by assuming some fraction of the thermal resource is recoverable (White and Williams, 1975). A complete numerical simulation of the coupled heat-flow and mass-flow equations for specified well and reservoir geometries can be attempted. Numerical simulations are complex and often involve so many adjustable parameters that it is often difficult to gain insight into a problem from such a solution. Our approach is to idealize the problem (see e.g., Bodvarsson, 1972) and consider only the essential aspects of the heat and mass transport as discussed below. In this way, a model is obtained which involves a small number of parameters and provides insight into the reservoir behavior during production.

The specific questions of interest are: 1) how much heat can be extracted from the reservoir rocks when reservoir fluid is produced with complete reinjection; and 2) how will the reservoir heat extraction be affected by the presence of fractures?

For a porous reservoir, essentially all of the heat above the reinjection fluid temperature can be removed from the rock. If fractures are present in the reservoir, they may short-circuit the injection-production process and cause a rapid temperature decline.

Our model of the system is represented by Fig. 1. The resource consists of three components: rock matrix, fluid in interstitial pore space, and fluid in the fractures (fissures, faults, etc.). The two fluids are represented by the single box in Fig. 1. Three coupled differential equations represent the idealized model. In defining the equations, we do not need to give the number or distribution pattern of the individual

geothermal wells. Rather, it is assumed that a system of production and injection wells exists which can accommodate the required flow rates for a specified level of power extraction from the fluid. In this summary, we consider only the case of fractures which are perpendicular to the wellbores of the production and injection wells. For vertical wells the fractures are assumed to be horizontal. If inclined (or horizontal) wells are drilled, the fractures are again perpendicular to the flow in the well system.

The fractures are modeled by a series of channels between parallel plates, as shown in Fig. 2. Two parameters are used to specify the fracture distribution, w , the aperture or opening of the fracture, and D , the distance between fractures.

The ratio of fracture fluid to pore fluid flowing into the production well is calculated from the assumed permeability of the porous slabs and the calculated permeability due to the fractures. The heat transfer from rock to pore fluid is given by the steady-state conduction equation. An exact calculation of the heat exchange from rock to fracture fluid is too difficult, because it would depend on the entire temperature history of the fluid passing the rock. We estimate that heat transfer term at any time from the instantaneous average temperature difference between the rock and the fracture fluid. This approximation is tested in results to be shown later (Fig. 5).

Calculated upper bound curves for the average temperature of a reservoir are shown in Fig. 3. The reservoir has the volume estimated for the Salton Sea KGRA (Towse, 1975). The flow rate from the production wells is sufficient to produce 1000 MW of electric power, assuming that 16% of the energy coming from the reservoir is converted to useful power.

If no fractures are present, the temperatures of the fluid and rock remain equal and the heat content decays exponentially. The time constant of the decay can be calculated from the total thermal mass of the rock and fluid. The top line in Fig. 3 represents the exponential decay, but the scale is expanded so that the line looks almost straight.

When fractures are present, the depletion curves are calculated by keeping the pore fluid and rock in equilibrium. We assume that the fractures communicate between injection and production wells. The fluid produced is a mixture of fracture fluid, which cools rapidly, and pore fluid, which cools slowly. The rapid decay of average temperature for the mixture is apparent in Fig. 3.

Although this very simple calculation leads to an appreciation of the effects of fractures on field lifetime, it does not represent a good upper bound for the useful lifetime of a geothermal reservoir because regions of cool re injected fluid are averaged with regions of hot fluid near production wells.

Fig. 4 shows how we estimate the temperature profile between the production and injection wells. The reservoir is represented by several volumes in series. Each volume may have a very complicated shape and is not necessarily singly connected. The fluid is assumed to move through the reservoir with no mixing, i.e., the first volume fills completely with

reinjection fluid before any reinjection fluid reaches the second volume. We choose a time-step sufficient to exchange fluid in one volume, solve for the temperature decline in each volume independently using the method described above, and then move the fluid to the next volume. In several steps, we can calculate the temperature decline at the last volume, which represents the region nearest the production well.

The most important assumption we have made is that the fluid moves without mixing, which is consistent with our desire to find an upper bound. To test our method, and our approximation of the heat-transfer between rock and pore fluid, we compared our calculations to the numerical results of Gringarten, et al. (1975), for hot dry rock with multiple fractures. As shown in Fig. 5, the two numerical methods agreed closely.

Fig. 6 shows our calculated wellbore temperatures for a resource with the volume of the Salton Sea Geothermal Field (SSGF) (Towse, 1975), and an effective power production of 400 MW. Power could be produced at that level for 20 years from the hot fluid alone. Our calculations for a porous medium with no fractures indicate a lifetime of up to 3.3 times as long, because of heat extraction from the rock.

Fractures cause a more rapid decline of production temperature. The calculated temperature drop after 20 years is used as a measure of the effect of fractures. In Fig. 7, that temperature drop is contoured for a variety of values of w and D . The dashed lines indicate different ratios of pore fluid and fracture fluid in the production well.

For small w or D , the depletion is the same as if fractures were absent. If more than 10% of the flow occurs in widely separated fractures, the wellbore temperature declines more rapidly. The depletion increases when

$$D > 50 \text{ m and } \frac{w^3}{D} > 2. \times 10^{-12} \text{ (m}^2\text{)}.$$

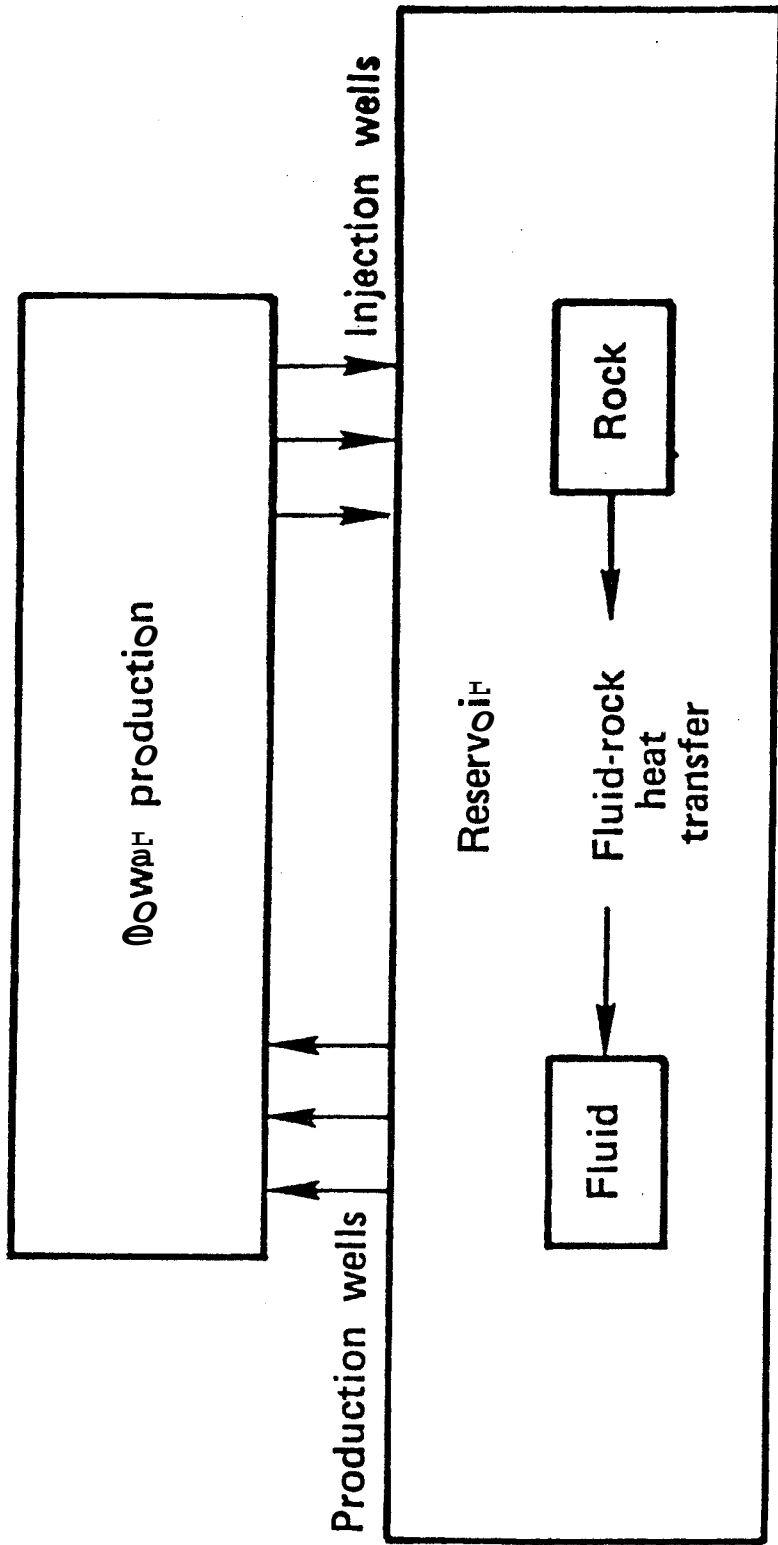
In summary, resource estimates should consider the heat in the rock matrix in addition to that in the geothermal fluid. Fractures may cause a significantly greater temperature decline than would be predicted from estimates based on porous flow alone. This result is very important for the design and production of a liquid-dominated hydrothermal system, because wells are targeted on fractures whenever possible, in order to increase the flow rate per well. Our results emphasize that if reinjection wells and production wells intersect the same fracture system, the useful lifetime of the production wells may be dramatically reduced.

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MODEL FOR RESERVOIR HEAT DEPLETION CALCULATION



Assume

- Constant reservoir mass
- Injection mass equals production mass
- No heat exchange with rock or fluid outside the reservoir
- Fluid consists of pore fluid and fracture fluid

FIGURE 1.

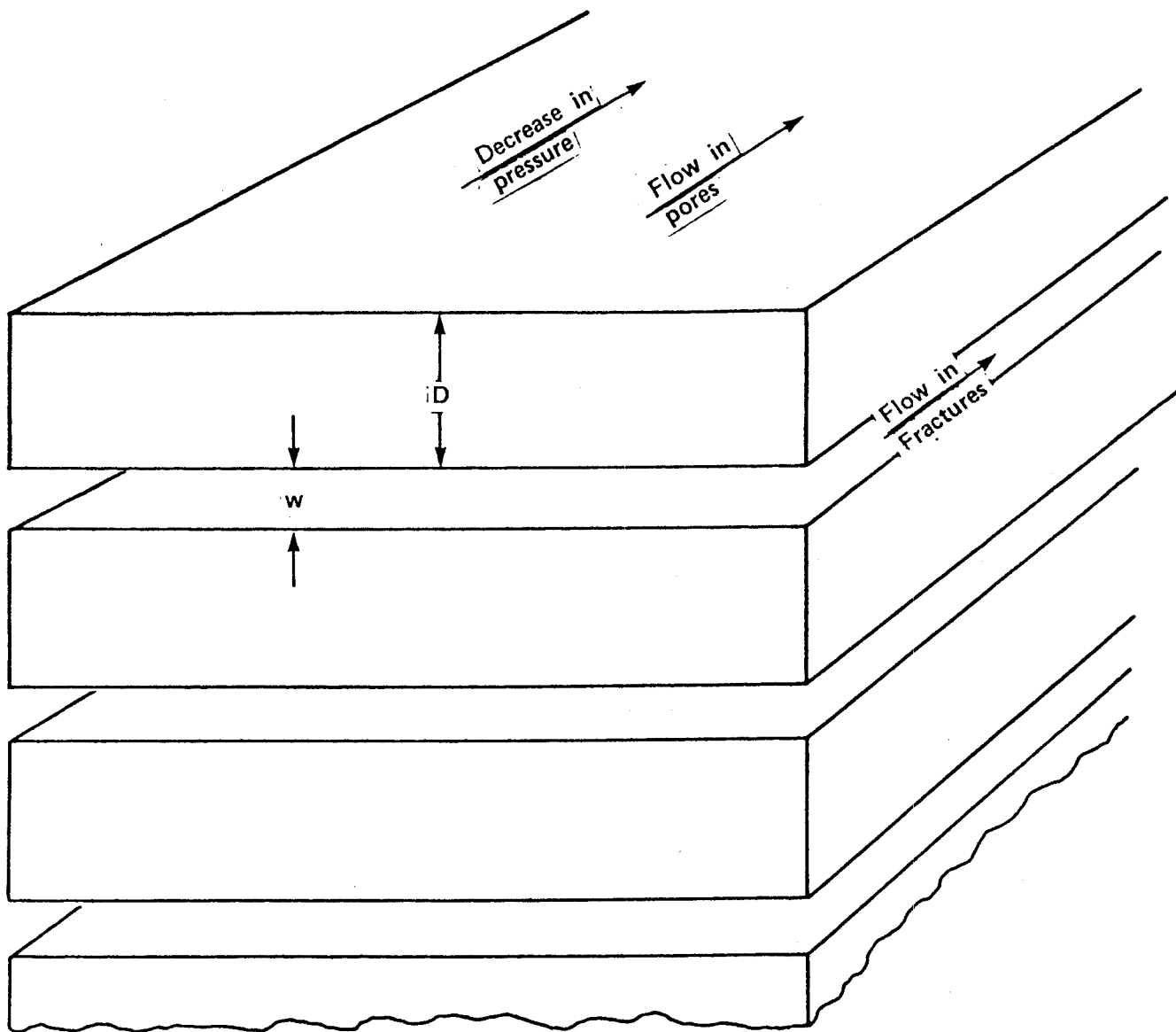


FIGURE 2.

A COMPARISON OF FRACTURE APERTURE FOR THE
SALTON SEA KGRA, 1000MWe, 1500 m FRACTURE
SPACING.

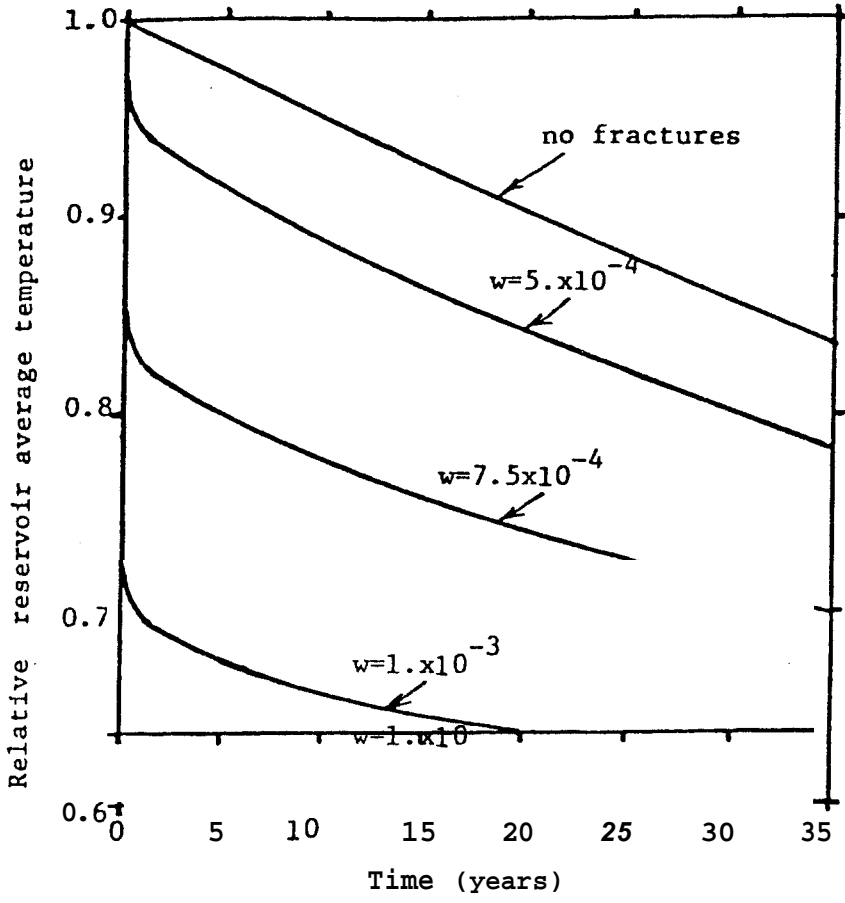


FIGURE 3.

 MODEL FOR CALCULATING TEMPERATURE DISTRIBUTION WITHIN RESERVOIR

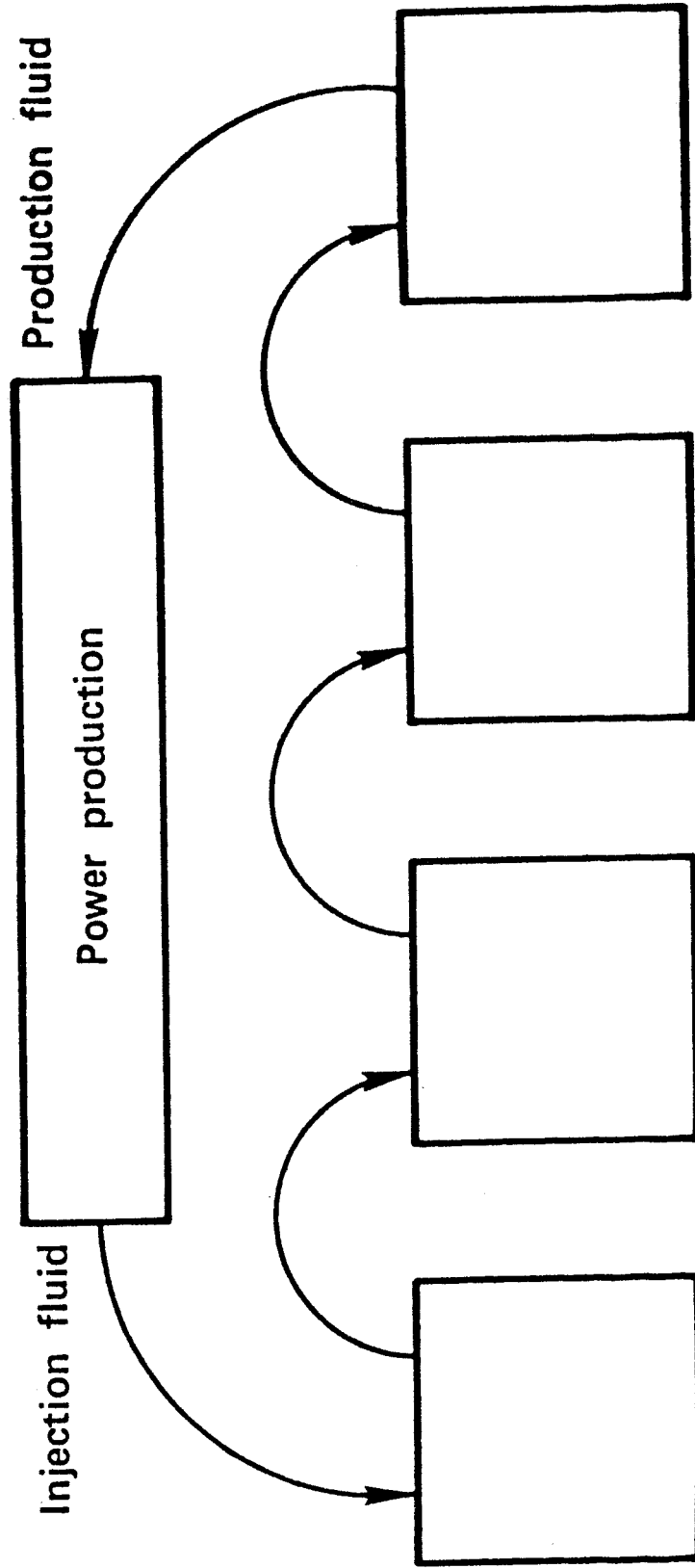


FIGURE 4.

HOT DRY ROCK WITH MULTIPLE FRACTURES RESULTS FROM TWO NUMERICAL METHODS

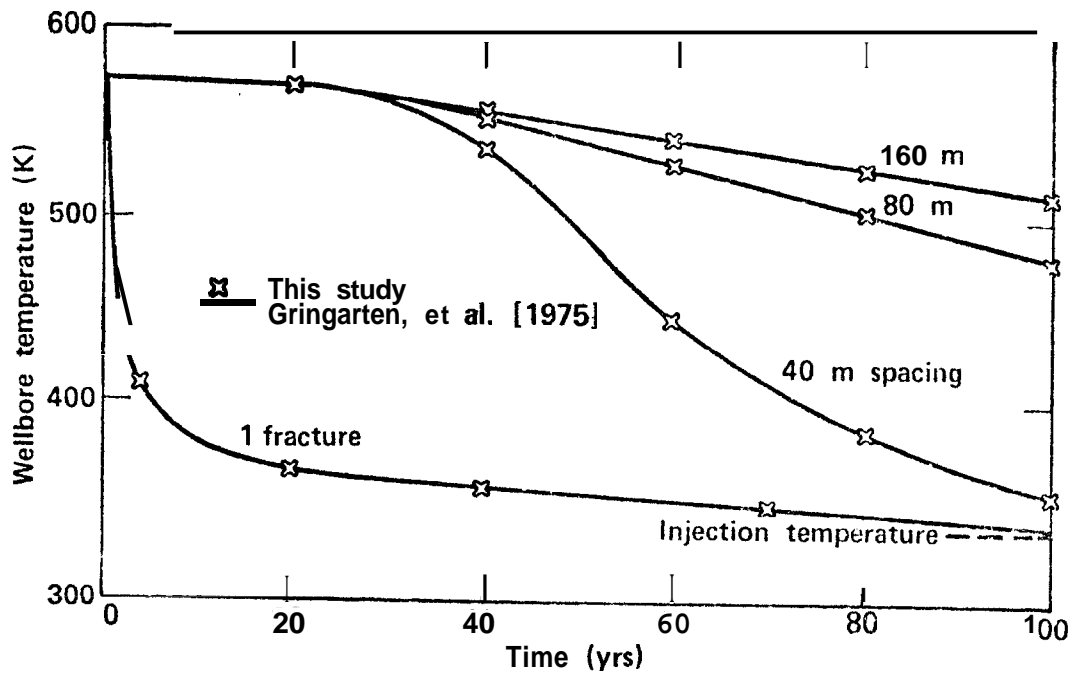


FIGURE 5.

WELLBORE TEMPERATURE vs. TIME
SSGF 400 megawatts initial power extracted (with fractures)

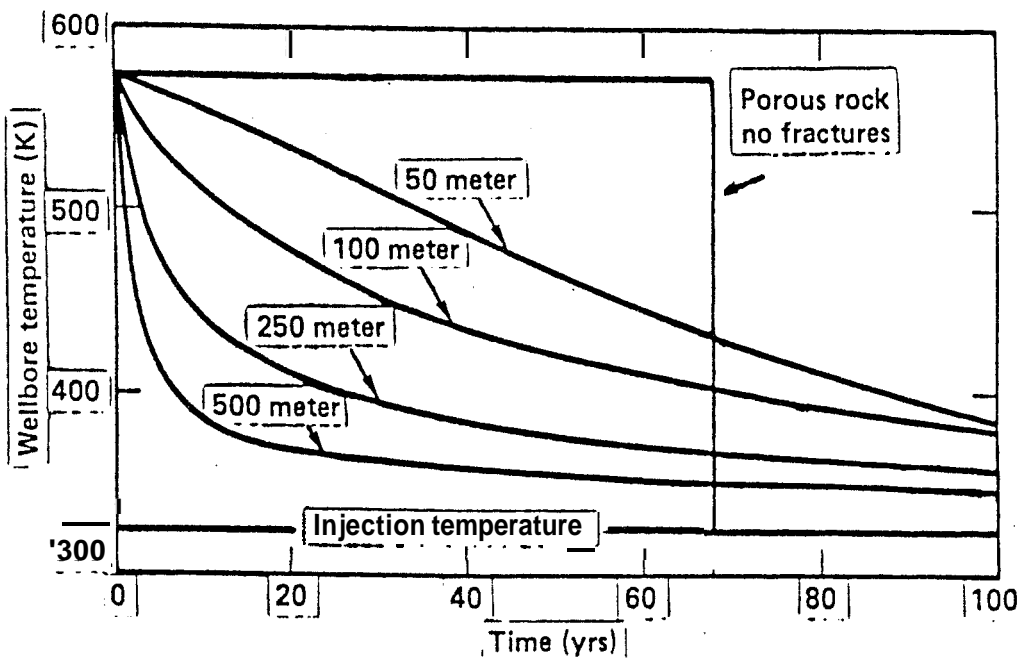


FIGURE 6.



**CONTOURS OF PRODUCTION FLUID TEMPERATURE
DECLINE AFTER 20 YEARS, FOR DIFFERENT
FRACTURE DISTRIBUTIONS (SSGF, 400MW)**

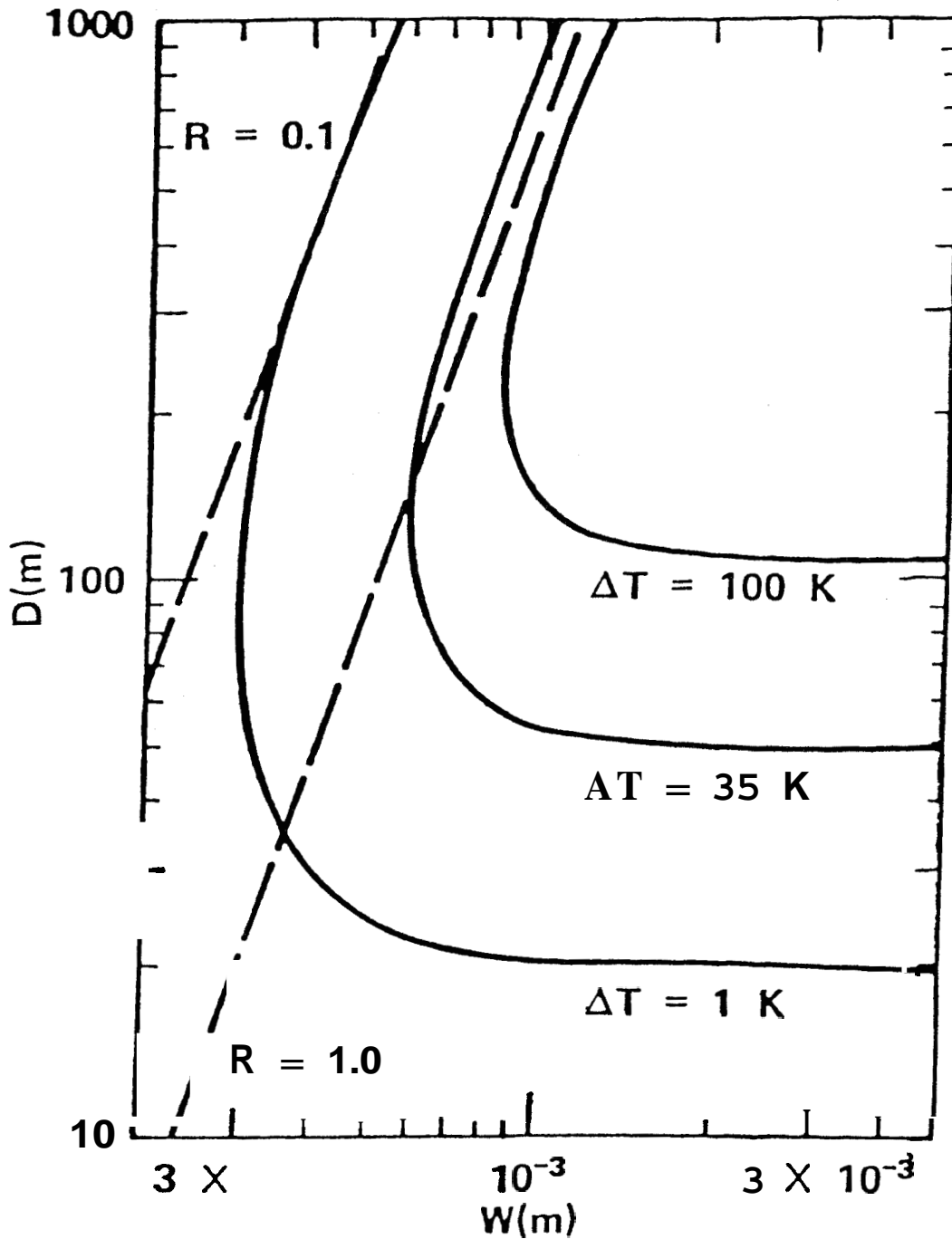


FIGURE 7.

GEOHERMAL ENERGY FROM A BOREHOLE
IN HOT DRY ROCK - A PRELIMINARY STUDY

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A simple procedure for calculating heat transfer between circulated water and hot dry rock in a single, concentric-annulus geothermal well is presented. Also presented are the results of an application of the procedure to a proposed well in Sweden.

The concept examined consists essentially of pumping water, at naturally-occurring temperatures, down a cylindrical well drilled several kilometers into the earth, and extracting it in a heated state through an annular cylinder (see for example, Smith *et al.*, 1973). Two different schemes embodying the same concept are examined in the present investigation. These are illustrated in Figs. 1 and 2. In the first, cold water is pumped into the inner cylinder and extracted through the annular space. In the second, the situation is exactly reversed.

The problem, in both schemes, is to predict the outlet temperature of water under given conditions on the one hand; and on the other, to predict the temperature drop in the rock mass surrounding the well, otherwise known as energy depletion of the geothermal reservoir. (See Gringarten *et al.*, (1975) for analytical solutions to a plane-crack situation embodying a similar concept.) Such prediction was undertaken in two stages.

Methodology Adopted

In order to render the problem tractable to simple mathematical analysis in Stage 1, certain simplifying assumptions are made. By virtue of these assumptions, the process of thermal energy gain by the flowing water was decoupled from that of energy loss by the surrounding rock mass. Then, an ordinary differential equation was formulated to represent the energy-gain process, and solved analytically with specified rock temperatures as boundary condition. A series of such solutions was obtained and the influence of significant parameters was investigated. During this stage, only a rough estimate of rock-mass energy depletion was made. This estimate indicated that such a depletion would be minimal.

In Stage 2, the coupled, and essentially unsteady-state, processes were modelled by partial-differential equations, which were solved by an integrated, finite-difference technique. A computer program embodying this technique was used to investigate the influence of significant parameters. Such investigations are continuing and the results presented here are preliminary.

Mathematical Details

1. Simplifying Assumptions

The following assumptions are made, in both Stage 1 and Stage 2 calculations, concerning the process of thermal energy gain by circulating water:

- a) The flow is fully-developed, i.e., essentially one-dimensional in nature, both within the inner tube and in the annular space.
- b) The flow is turbulent.
- c) Within the temperature range encountered, the circulating-water properties remain essentially constant.
- d) The rock-mass temperature varies linearly with depth below the earth's surface.

2. Stage 1 Calculations

The ordinary differential equation governing the steady-state energy gain by circulating water in Scheme I is

$$\frac{dT_W}{dx} + \left\{ \frac{hP}{\dot{m}C_W} \right\} T_W = \left\{ \frac{hP}{\dot{m}C_W} \right\} (T_{R,L} - ax) \quad (1)$$

and, in Scheme II is

$$\frac{dT_W}{d\xi} + \left\{ \frac{hP}{\dot{m}C_W} \right\} T_W = \left\{ \frac{hP}{\dot{m}C_W} \right\} (T_{R,0} + a\xi) \quad (2)$$

The symbols in the above equations are defined in Fig. 3, and in the nomenclature'. The solution to Equation (1) is (Sharma, 1975)

$$T_W = T_{W,0} e^{-\left\{ \frac{hP}{\dot{m}C_W} \right\} x} - ax + \left[T_{R,L} + a \left\{ \frac{\dot{m}C_W}{hP} \right\} \right] \left(1 - e^{-\left\{ \frac{hP}{\dot{m}C_W} \right\} x} \right) \quad (3)$$

and to Equation (2) is

$$T_W = T_{W,0} e^{-\left\{ \frac{hP}{\dot{m}C_W} \right\} \xi} + a\xi + \left[T_{R,0} + a \left\{ \frac{\dot{m}C_W}{hP} \right\} \right] \left(1 - e^{-\left\{ \frac{hP}{\dot{m}C_W} \right\} \xi} \right) \quad (4)$$

These solutions, obtained with known values of rock temperature, are represented in Figs. 4 and 5. In order to make these representations, the values of heat-transfer coefficient h were extracted from the work of Kays and Leung (1963). Furthermore a borehole of 4 in. was presumed and a thermal gradient " α " of 0.034.

It can be observed from Fig. 5 that Scheme II is preferable to Scheme I. However, the influence of circulating water flow in cooling the adjacent rock and hence depleting the geothermal energy source cannot be observed by the decoupled technique. In order to calculate this depletion, it is necessary to perform calculation of the coupled processes.

3. Stage 2 Calculations

The Stage 2 calculations involved the solution of the coupled problem. This problem is expressed mathematically thus:

Circulating-water energy gain

$$\rho_w c_w \frac{\partial T_w}{\partial t} + \rho_w c_w U_w \frac{\partial T_w}{\partial \xi} = \frac{2h}{R_I} (T_R - T_w) \quad (5)$$

with the initial and boundary conditions:

$$\begin{aligned} T_w &= T_{w,0} , & 0 < \xi < L ; & t < 0 \\ &= T_{w,0} , & \xi = 0 , & t \geq 0 \end{aligned} \quad (6)$$

Rock-mass energy loss

$$\rho_R c_R \frac{\partial T_R}{\partial t} = \frac{\partial}{\partial \xi} \left(k_R \frac{\partial T_R}{\partial \xi} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(k_R r \frac{\partial T_R}{\partial r} \right) \quad (7)$$

with the initial and boundary conditions:

$$\begin{aligned}
 & T_R(\xi) = T_{R,0} + a\xi, \\
 & \left. \begin{aligned} & 0 < \xi < L \\ & R_I < r < R_0 \end{aligned} \right\}; t < 0 \\
 & T_R = T_{R,0} \\
 & \left. \begin{aligned} & \bar{T}_R(\xi) \\ & r = R_0 \end{aligned} \right\} \geq 0 \\
 & -k \frac{\partial T_R}{\partial r} = h(T_W - T_R), \quad r = R_I, \quad t \geq 0
 \end{aligned} \tag{8}$$

The coupled solutions to Equations (5) and (7) with boundary conditions (6) and (8) were obtained with an integrated finite-difference procedure described by Sharma (1975). Investigations in this connection are still continuing. However, a result of the application of the procedure to Scheme II (Fig. 2) is illustrated in Fig. 6. This result appears to indicate that the rock-face temperature drops more rapidly due to the circulating-water energy gain, than the replenishment possible due to heat conduction from the surrounding rock mass. It is clear that a simple borehole type of approach is not sufficient for extracting geothermal energy in meaningful quantities. It is concluded from the present study that either explosives or hydraulic fracturing will have to be used in order to provide sufficient contact area for effective energy extraction. In countries such as Sweden where abnormally high horizontal stresses exist, it is likely that horizontal fractures can be created, thereby providing a vast surface area of contact at constant high temperature (this is clearly an advantage over other parts of the world where vertical fractures are more common). We are currently studying the problem of geothermal energy gain from circulating water flow through arbitrarily-shaped fractures. This study is based upon a mathematical model involving the numerical solution of partial differential equations governing convective heat and mass transfer. In a continuing study, account will be taken of phase change, dissolution, turbulence and other influences on thermal energy transfer.

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Nomenclature

a	-	geothermal gradient
C_R, C_W	-	specific heat capacity of rock mass and circulating water respectively
h	-	water-rock surface heat-exchange coefficient
L	-	depth of borehole
\dot{m}	-	circulating water mass flow rate
\dot{p}	-	perimeter of borehole
$r,$	-	radius coordinate
R_I, R_O	-	radii of borehole and rock mass considered respectively
t	-	time coordinate
U_W	-	velocity of circulating water
ξ	-	depth coordinate
ρ	-	density
x	-	inverse depth coordinate

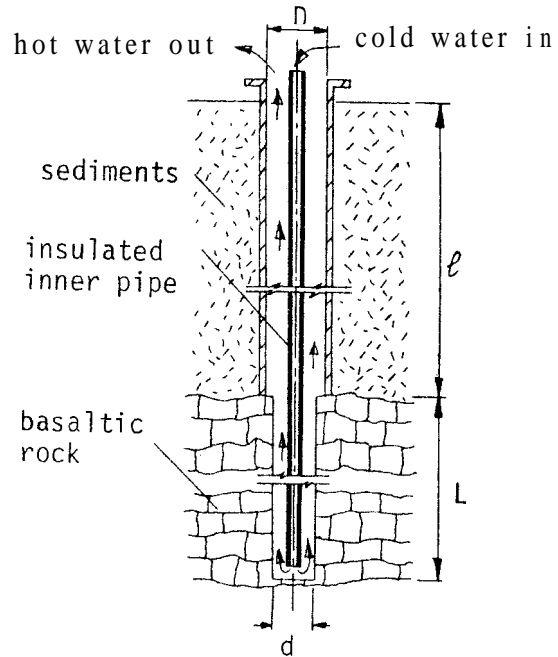


Fig. 1 Illustration of geothermal well; Scheme I.

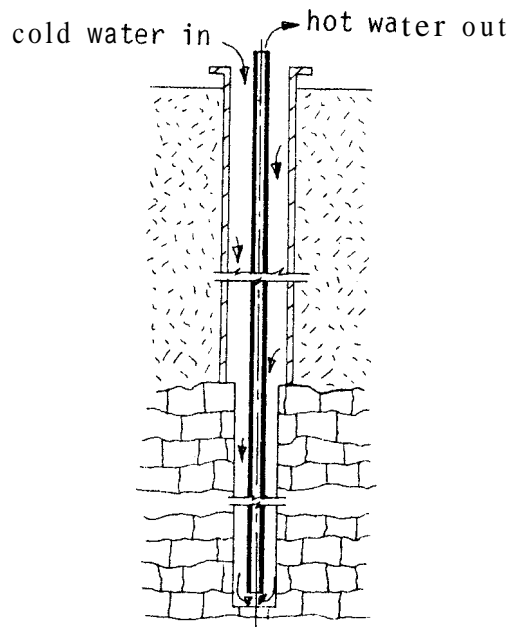
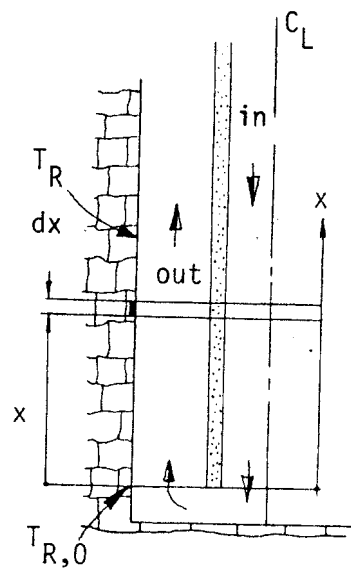


Fig. 2 Illustration of geothermal well; Scheme II.



(a)

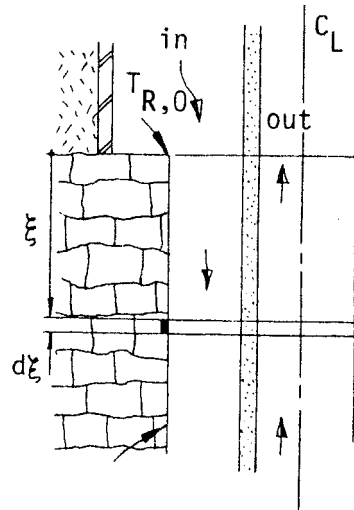


Fig. 3 Illustration of coordinate system.

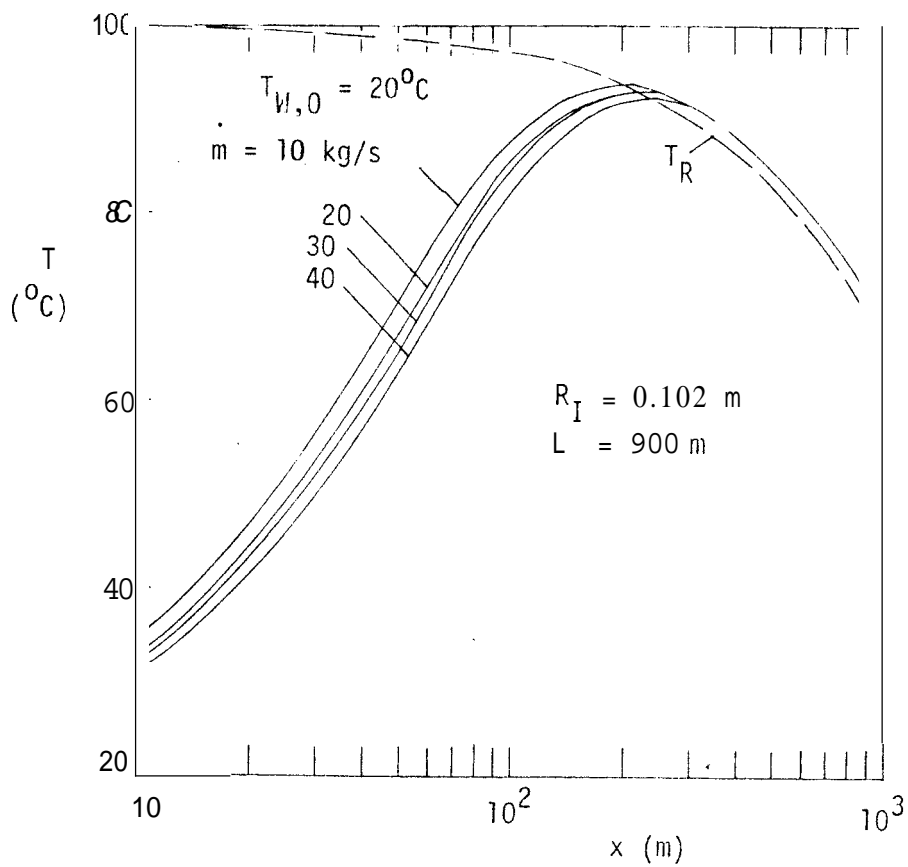


Fig. 4 Effect of flowrate on temperature rise of circulating water, Scheme I.

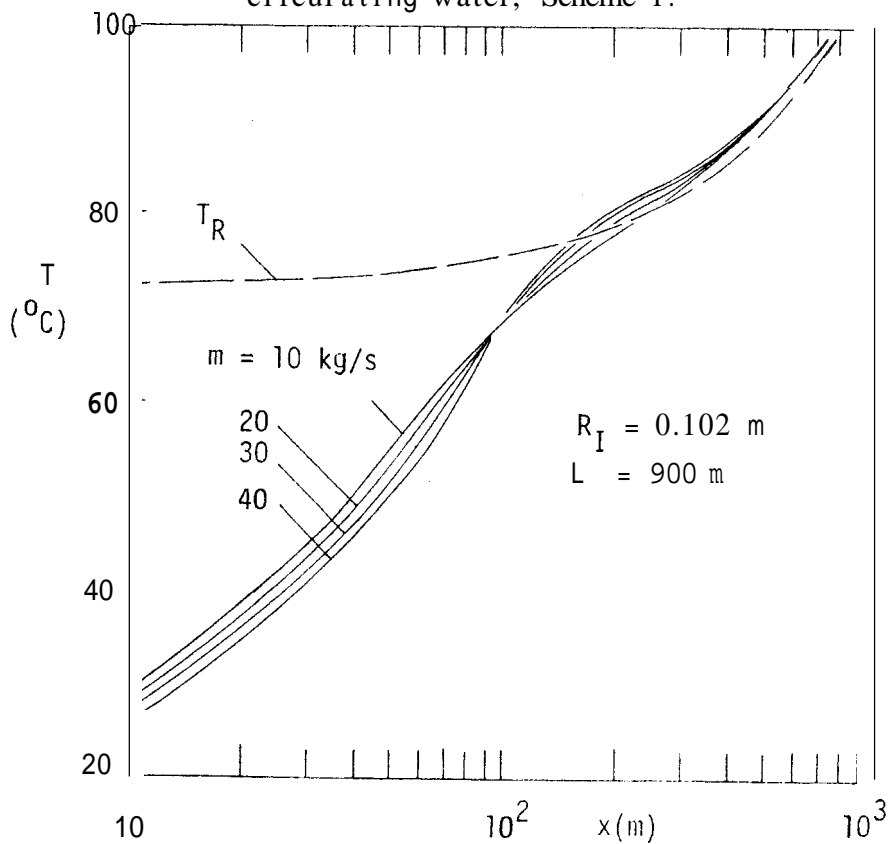


Fig. 5 Effect of flowrate on temperature rise of circulating water, Scheme II.

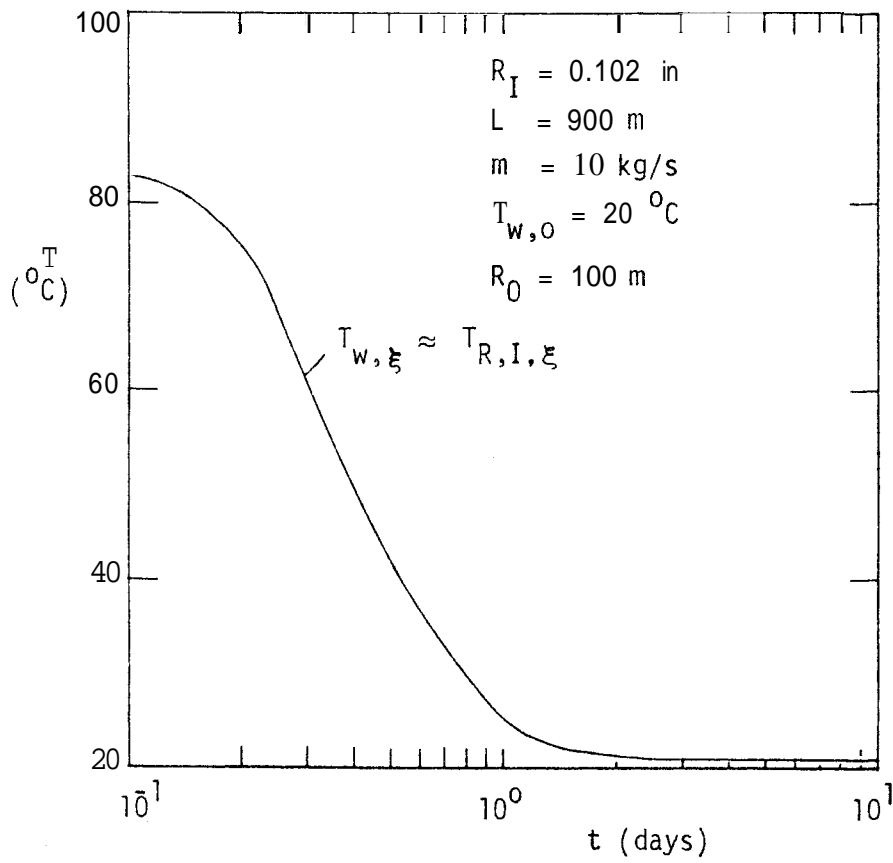


Fig. 6 Outlet temperature of circulating water; coupled problem.

THE USE OF GENERAL SENSITIVITY THEORY TO ANALYZE THE GEOTHERMAL RESERVOIR MODEL'S SENSITIVITY TO THE PERMEABILITY FUNCTIONS

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Sensitivity theory is concerned with studying how a model depends upon its parameters, constants or functions. Models of real physical processes, such as flow in a geothermal reservoir, are implemented via numerical simulations. The results of the model u are available only for certain values of the parameters p_0 . Because the exact dependence of u on p is not known, sensitivity studies are typically done by random or quasi-organized searches of the parameter space p , and computer output is generated for sets of points p_0 for the parameters.

The mapping $u(p)$ and its derivatives are of great interest. The derivatives are defined to be sensitivity functions. For constant parameters, the sensitivity functions are $\frac{\partial u_i}{\partial p_j}$ and for parametric functions $u_p \cdot \delta p$ where $u_p \cdot$ is the Frechet derivative of $u(p)$, and δp is a vector of perturbation functions.

I have developed a general sensitivity theory (1,2,3) which allows the formation of an auxiliary or dual model from which the sensitivity functions can be calculated directly. Thus, the state and sensitivity functions can be generated for "likely" values of p , and the sensitivity functions indicate how u will change for changes in p in the neighborhood of p_0 .

In the following sections I will summarize general sensitivity theory and its usefulness by presenting two examples from reservoir modeling.

General Sensitivity Theory

The derivation of the general sensitivity theory is based upon the use of the implicit function theorem for operators on Banach spaces. I view the model as

$$N(u,p) = 0 \tag{1}$$

Then the implicit function theorem asserts the existence of $u(p)$ such that

$$N(u(p), p) = 0 \tag{2}$$

We now differentiate (2) in the sense of Frechet to get

$$N_u^i \cdot u_p^i + N_p^i \cdot \delta p = 0 \quad (3)$$

In the case of constant parameters (3) becomes

$$N_u^i \cdot \left\{ \frac{\partial u_i}{\partial p_j} \right\} + N_p^i = 0 \quad (4)$$

We will exhibit specific examples in the next section.

Flow in Anisotropic Porous Media

For the model 1 take the following set of equations (4)

$$\nabla P + \mu \underline{\underline{D}} \cdot \underline{\underline{V}} = 0 \quad (5)$$

$$A \cdot \underline{\underline{V}} = 0 \quad (6)$$

Where $\underline{\underline{V}}$ is the superficial velocity. $\underline{\underline{D}}$ is the dispersion tensor;

$$\underline{\underline{D}} = \underline{\underline{K}}^{-1}, \text{ and } \underline{\underline{K}} \text{ is the permeability tensor. Equations}$$

(5) and (6) define a model $\underline{\underline{R}}(\underline{\underline{u}}, p)$ where $\underline{\underline{u}} = (V_1, V_2, V_3, P)$ and

$$P = (D_{11}, D_{12}, D_{13}, D_{22}, D_{23}, D_{33}).$$

Computing derivatives R_u^i and R_p^i

$$R_u^i = \begin{bmatrix} \mu \underline{\underline{D}} \cdot \underline{\underline{V}} \\ \frac{\partial}{\partial x_1} & \frac{\partial}{\partial x_2} & \frac{\partial}{\partial x_3} \end{bmatrix}$$

$$R_p^i = \begin{bmatrix} V_1 & V_2 & V_3 & 0 & 3 & 0 \\ 0 & 0 & 0 & V_2 & V_3 & 0 \\ 0 & 0 & 0 & 0 & V_2 & V_3 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Let $\phi = u_p^i \cdot \delta p$

Then we have 24 sensitivity equations in the form

$$R_u^i \cdot \phi + R_p^i \cdot \delta p = 0$$

where δp are the perturbations in the dispersion or permeability functions, and $\phi = 0$ on the boundary of the domain.

Because R is linear in u , the sensitivity and the model are governed by the same basic operator.

A Nonlinear Example

For a nonlinear example, I turn to a model of Peaceman and Rachford [5].

$$\frac{\partial}{\partial x} \left[\frac{k_x}{\mu} \left(\frac{\partial p}{\partial x} - \delta \frac{\partial z}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[\frac{k_y}{\mu} \left(\frac{\partial p}{\partial y} - \delta \frac{\partial z}{\partial y} \right) \right] = \quad x, y) \quad (7)$$

$$\frac{\partial}{\partial x} \left(D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial c}{\partial y} \right) - u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y} = \phi \frac{\partial c}{\partial t} \quad (8)$$

k_x, k_y, ϕ are functions of x and y only.

Nonlinearities are introduced via

$$\mu = f(p, c) \quad \gamma = f(c) \quad (9)$$

In addition

$$D_x = D + \frac{\alpha_x}{\phi} |u_x|$$

$$D_y = D + \frac{\alpha_y}{\phi} |u_y|$$

The state is given by $u = (p, c)$ and the parameters of $\tilde{p} = (k_x, k_y)$

I will not write out R'_u and R'_p . However, it is of interest to note that because of the nonlinear coupling, σc can affect p even if u_p is zero; and conversely.

Summary and Conclusions

I have briefly sketched sensitivity theory and its application to two problems. A key point to recognize is that the sensitivity model is the complement of the physical model. A powerful result is that regions in ρ of unusual behavior for u can be found more easily from studying the behavior of the sensitivities than from studying u alone. This observation is true even in cases where $u(\rho)$ is known.

I expect the techniques of general sensitivity analysis to be useful in formulating and using geothermal reservoir simulators under conditions of large parameter uncertainty.

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