THE GEOTHERMAL PROGRAM AT LAWRENCE BERKELEY LABORATORY

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ABSTRACT

The main purpose of the geothermal program at Lawrence Berkeley Laboratory is to develop, improve and validate methods and instrumentation to: (1) determine geothermal reservoir parameters; (2) detect and characterize reservoir fractures and boundaries; and (3) identify and evaluate the importance of reservoir processes. The ultimate objective of the program, which includes field, theoretical and modeling activities, is to advance the state-of-the-art for characterizing geothermal systems and evaluating their productive capacity and longevity under commercial exploitation.

INTRODUCTION

The multidisciplinary geothermal program at Lawrence Berkeley Laboratory (LBL) is being funded mainly by the Geothermal Technology Division (GTD) of the Department of Energy (DOE). Additional support has been obtained from the California State Lands Commission for the evaluation of The Geysers, California, field (Bodvarsson et al., 1986a). In this review paper we only describe our most recent (1986/87) activities sponsored by DOE/GTD.

RESERVOIR ENGINEERING

The major focus of the LBL geothermal program is to develop well testing techniques, laboratory methods and mathematical modeling codes to analyze and evaluate geothermal reservoirs. Under study are various reservoir engineering methods to characterize and simulate the dynamic behavior of single-phase and two-phase geothermal systems under natural and exploitation conditions, with constant or changing fluid compositions and fractured or porous reservoir rock conditions. Another aspect of the program is to improve our capability to numerically simulate the response of geothermal systems to cold wastewater injection taking into consideration physical and chemical effects. These methods, developed to monitor and predict the behavior of the reservoir, will allow us to optimize the design of production and injection operations for extracting the heat stored in the subsurface rocks.

Physics and Chemistry of Fluid Extraction and Reinjection

In order to: (1) determine the characteristics of geothermal reservoirs; (2) effectively analyze the measurements made at the surface and downhole; and (3) predict the changes resulting from the exploitation of geothermal systems, it is necessary to have a good understanding of the complex processes occurring in the reservoir. Theoretical and modeling studies are performed to evaluate the importance of different phenomena in geothermal systems. For the purpose of simulating a number of important reservoir processes it was necessary to improve the capabilities of some of LBL's computer codes.

The mass and energy recovery from tight rock matrix blocks of fractured geothermal reservoirs is of considerable interest to industry. By way of modeling studies it was found that non-condensible gases can greatly affect the mass recovery, with less mass being recoverable if these gases are present in the reservoir (Gaulke, 1986; Bodvarsson and Gaulke, 1987). Analytical expressions quantifying the effects of non-condensible gases on mass and energy recovery have been developed.

Geochemistry of non-condensible gases is a topic of great current interest in the study of two-phase geothermal reservoirs. Recent work in this area has defined possibilities for estimating in-place phase compositions of reservoir fluids from gas analysis data. The effects of transport processes on produced gas compositions have been studied (D'Amore and Pruess, 1986).

The temperature range of LBL's MULKOM simulator (Pruess, 1983) is being extended to near-critical and supercritical conditions (374 °C and beyond), to attain a capability for modeling heat transfer in deep zones of geothermal systems. Initial results are encouraging, indicating strong enhancements in convective and dispersive heat transfer near the critical point.

Numerical simulation methods have been used to investigate gravity effects on reservoir pressure transients and depletion patterns in two-phase reservoirs (Bodvarsson and Cox, 1986). These studies showed that production from a deep feed zone gives rise to an efficient gravity drainage mechanism that causes only gradual long-term pressure changes at the well. On the other hand, because of gravity effects, production from shallow feeds results in considerably higher pressure drawdowns.

A wellbore simulator has recently been developed to model one- or two-phase flow in a vertical geothermal well fed by two or more production zones (Bjornsson, 1987). The governing equations are solved numerically by finite difference methods, assuming steady state flow in the well. Either wellhead or wellbottom flowrates, enthalpies and pressures are given as boundary conditions. Well geometry and the feedzone properties have to be specified. The simulator can handle variable diameter wells, injection and production, and internal flow.

The highly heterogeneous and faulted nature of geothermal systems makes the application of conventional well testing analysis methods for parameter assessment unreliable. New techniques, tailored to the type of heterogeneity typical of geothermal systems, are needed. LBL has developed a new method for locating and assessing the size and permeability of high-permeability regions within reservoirs (Benson and Lai, 1986). The method was successfully applied to the Klamath Falls geothermal system.

In cooperation with Italian researchers, LBL studied cold water injection into depleted two-phase reservoirs (Calore et al., 1986). It was determined that injection plumes migrate primarily downward rather than outward. An efficient heat extraction mechanism is provided by heat pipe effects on the boiling surface of the plume. The results of this study indicate that the prospects for enhanced energy recovery by means of injection into depleted two-phase zones are excellent.

Heat extraction experiments using a large-scale laboratory model at Stanford University have been successfully modeled with the computer code MULKOM (Pruess, 1983) using the "Multiple Interacting Continua" (MINC) method (Pruess and Narasimhan, 1985). This work, carried out in collaboration with Stanford researchers, validated the methodology used for modeling the behavior of two-phase systems with complex geometry and boundary conditions (Lam et al., 1987).

Cold water injection into two-phase or vapor zones can give rise to sharp (hydrodynamic, chemical, thermal) fronts. Numerical simulation of processes involving these fronts is difficult, and the accuracy of the most commonly used methods (finite difference, finite element) is questionable. Pruess et al. (1987a) obtained an analytical solution to an injection problem involving a moving boiling front which can be used to verify numerical simulators and to obtain approximate estimates of field response.

Major problems in modeling sharp fronts are numerical diffusion errors and grid orientation effects. Both of these cause an artificial smearing of the fronts, yielding unreliable results for analysis of field data. Lai et al. (1986) developed a finite difference method for modeling sharp fronts that consists of an explicit second-order Godunov method and the operator splitting technique. It was found that this method practically eliminates numerical diffusion errors and grid orientation effects, thus providing a tool for reliable analysis of thermal interference and tracer well test data.

Analysis of Geothermal Fields under Exploration or Development

Data from U.S. geothermal fields has been continually gathered by LBL. This work is done as part of the studies funded by DOE in cooperation with federal and state agencies (e.g., hydrogeologic studies of Klamath Falls and Crater Lake, Oregon), or by means of joint DOE/industry-sponsored projects (e.g., injection tests at East Mesa, California). Furthermore, through the formal agreement between DOE and CFE of Mexico, as well as through informal cooperation with foreign R&D groups, LBL has been able to acquire information from a number of high- and low-temperature geothermal fields throughout the world (e.g., Cerro Prieto and Los Azufres, Mexico; Ellidaar, Seltjarnarnes and Svartsengi, Iceland; Larderello, Italy; Olkaria, Kenya).

The purpose of these activities is: (1) to assist DOE with its cooperative field projects with U.S. industry, state organizations, and Mexico; (2) to continue the field validation of the technology developed under the DOE Geothermal Program; (3) to add to our understanding of the processes occurring in geothermal systems in their natural and exploited state; and (4) to transfer to U.S. industry and the geothermal community in general, information on the exploration and development of geothermal systems of different characteristics, and their response to exploitation. A short description of these field-related studies follows; in many instances the data analysis was done with the help of computer modeling techniques (e.g., Bodvarsson et al., 1986b) developed with DOE's support.

Klamath Falls. A reevaluation of the significant amount of information available on the Klamath Falls geothermal system was completed. Supported by borehole, geochemical, geophysical and hydrological data, a conceptual model of the area was developed (Prucha et al., 1987). Two main aquifers are present in the field, interconnected by a number of normal faults. At depth the system may be recharged by hot waters from the east and west; at shallow depths the thermal waters spread laterally through permeable layers and mix with colder regional groundwaters. Further work is required to determine the role of the different faults in the development and dynamics of this geothermal field.

Crater Lake. The geothermal/hydrogeologic system of Crater Lake was modeled by LBL. The numerical simulations indicated that: (1) the significant recharge derived from the caldera lake plays a dominant role on the hydrology of the surrounding region; and (2) the injection of drilling mud that might result from the proposed drilling activities in the Winema National Forest will not pose a threat to the lake or affect the hydrologic system in the immediate vicinity of the Crater Lake caldera (Sammel and Benson, 1987).

East Mesa. During July 1987 LBL is planning to carry out a joint Industry/DOE injection test at the GEO Operator Corporation (GEO) East Mesa site. This field project will help validate nonisothermal well testing techniques developed under DOE sponsorship. LBL will provide downhole instrumentation and analyze the test data to determine the parameters of the injected formation and track the front of injected fluids.

Cerro Prieto. The updating of the hydrogeologic model of Cerro Prieto continues. As information becomes available, lithological, thermal and completion data from new exploration and development wells are incorporated into the model. Recent data allowed delineation of the beta reservoir in the eastern part of the field, and confirmed the important role of normal fault H in controlling the flow of geothermal fluids in that region (Halfman et al., 1986). A recently completed review paper summarizes the geological, geochemical and reservoir engineering characteristics, and the exploitation history of Cerro Prieto (Lippmann and Mañón, 1987).

A careful study showed that contrary to earlier suggestions, the geochemical and reservoir engineering data from the shallow Cerro Prieto alpha reservoir cannot confirm the hypothesis of a massive influx of hot water into the system related to two large local 1979-80 earthquakes (Truesdell and Lippmann, 1986). The analysis of the information showed that the cold water recharge to the shallow reservoir in response to production-induced drawdown continues, unaffected by these earthquakes.

Los Azufres. Test data from geothermal wells at Los Azufres indicate that the permeability of the near-bore region increases during cold water injection. A newly developed analysis method (Benson et al., 1987) indicates that during a 2- to 3-hour long injection period the permeability increases by a factor of about five. A good correlation between the permeability increase and the sandface injection temperature suggests that this increase is related to the cooling of the formation. Thermal contraction and thermal stress cracking are the most probable causes of the near-bore permeability enhancement. Research on this topic continues.

Ellidaar/Seltjarnarnes. The Ellidaar and Seltjarnarnes fields are supplying geothermal fluids for space heating in Reykjavik, the capital of Iceland. The transport of heat, mass and chemical species in these low-temperature systems was simulated using computer programs developed at LBL (Lai, 1985; Spencer, 1986; Tulinius et al., 1987). It was possible to validate the models against observed temperature, pressure and chemical data. In the case of Seltjarnarnes the results of the simulations revealed regions of contrasting permeabilities and porosities, and suggested the possible encroachment of colder seawater into the reservoir.

Svartsengi. A new conceptual model of the Svartsengi field was developed (Bodvarsson, 1987). In contrast to earlier models, this model includes the effects of a two-phase zone overlying the main geothermal reservoir. A simple radial model was used to obtain a history match with the pressure decline observed in the reservoir during the 1979-83 period.

Larderello. In cooperation with Italian researchers, a preliminary analysis of the permeability structure and fluid and heat flow conditions in the deeper horizons of the Larderello system was completed (Pruess et al., 1987b). From an analysis of heat transfer mechanisms it was inferred that under natural state conditions a transition from vapor-dominated to liquid-dominated conditions must have occurred; that transition could have occurred at a depth of about 2000 m or more. It was also found that in deep high-temperature zones ($T>300°C$) vapor-liquid counterflow provides efficient heat transport at temperatures up to 350°C. This work indicated that from temperature-depth data in two-phase reservoirs the estimation of vertical permeability in the reservoir might be possible.

Olkaria. A detailed 3-D model of the East Olkaria well field was developed (Bodvarsson et al., 1987a). It matched reasonably well flow rate and enthalpy data from all existing wells. This modeling study suggests that the reservoir system is of rather uniform permeability with the possible exception of a high permeability north-south anomaly below 1000 m depth. A well-by-well model was then used to investigate various reservoir development schemes (Bodvarsson, et al., 1987b). The analysis focused on evaluating the effects of different well spacings on well deliverabilities and total electrical power production, and the effects of injection on well performance and reservoir depletion.

Development and Application of New Reservoir Engineering Instrumentation

Pressure transient tests are the most precise means of measuring the hydrologic properties of a geothermal formation. Present-day methods of analyzing these tests require extremely accurate pressure data measured at short time intervals. The high temperature of geothermal systems precludes the use of conventional instruments for making these measurements. LBL has developed and tested a high-resolution, high-speed, computer-controlled system for collecting interference and injection test data. The system is far superior to its commercially available counterparts and opens new doors for collecting the types of data needed to fully understand geothermal systems. The characteristics of this system are described by Benson (1986).

LBL's downhole fluid sampler (Solbau et al., 1986) was successfully used in the Salton Sea Scientific Drilling Project well. On the first and only downhole run, a sample was collected at a depth of about 3000 m, where the temperature was approximately 350°C. A 2-liter capacity and improved version of this sampler is scheduled to be ready for testing in July 1987.

GEOPHYSICS

The geophysical segment of the LBL geothermal program involves the development and testing of instrumentation, field techniques, and data processing and interpretation. Under investigation are advanced seismic and electromagnetic techniques for fracture detection and for reservoir delineation and mapping. Surface, surface-to-borehole, and cross-hole techniques are being studied. LBL supported several critical studies in processing, modeling and interpretation of data from the Long Valley caldera, California.

Fracture Detection and Mapping

Because many geothermal systems occur in highly heterogeneous and fractured rocks, a key element in the targeting of production wells is to determine and understand how and where the reservoir rocks are fractured. To this end, geophysicists at LBL have been analyzing and testing several techniques by means of numerical analyses and field experiments.

LBL has collected and analyzed 25 different vertical seismic profiling (VSP) offsets for geothermal wells at The Geysers (Majer et al., 1987), the Salton Sea, and in

Japan. Another 15 offsets of VSP data were taken in non-geothermal volcanic and crystalline rock environments. Using both compressional (P) and shear (S) wave sources, LBL is attempting to understand how VSP data are related to fundamental properties of the rocks and fluids; e.g., fracture density and the orientation of dominant fractures, liquid saturation, and hydrothermal alteration. A three-component survey was carried out with Unocal at The Geysers to a depth of about 2600 m. Anomalous wave characteristics could be correlated to the steam zone and specific steam entries.

Tomographic inversion techniques are being applied to VSP and natural microearthquake (MEQ) data as a means of mapping the 2-D and 3-D distribution of seismic velocity, a parameter that is related in part to fracture density. To make fuller use of tomographic results, we are studying the effects of fracture aperture and fracture stiffness on the propagation of P and S waves through rock samples.

Although MEQ monitoring surveys have been conducted at many geothermal fields, the cause of the seismicity and the relationships between seismicity, reservoir dynamics, tectonic stresses, known faults, and fluid circulation/recharge are seldom understood. GEO has installed a 16-station, three-component array of geophones over its field in the northwest Geysers area for baseline seismic data prior to the start-up of full-scale production. LBL is working with GEO to interpret the MEQ activity in terms of present reservoir conditions.

LBL is also cooperating with Geysers Geothermal Company (GGC) in their MEQ monitoring program of the south Geysers area. In late May 1987 LBL attached its Automatic Seismic Processor (ASP) system to GGC's seismic array and will record data for about six months. The analysis of the ASP data is being carried out by a University of California, Berkeley, student supported by GGC.

In a related study over a producing portion of The Geysers field, O'Connell (1986), funded by DOE's Office of Basic Energy Sciences (BES), completed a Ph.D. thesis in which he developed and applied a progressive inversion technique to three-component MEQ data to obtain Vp, Vs, and Vp/Vs variations with depth. He showed that the Vp/Vs structure is strongly controlled by the degree of liquid saturation. The location of the seismicity could also be explained by reservoir dynamics. Shallow seismicity from within the production zone may be due to mass withdrawal and amplification of subsidence and contraction effects. The deeper zone of earthquakes, well below the production interval (3 to 3.5 km below sea level), may be associated with hydrothermal fluid migration from a deep reservoir to the production zone via a series of vertical fractures.

The second part in a series of numerical modeling studies was completed as part of the LBL effort to evaluate the detection of conductive fractures by means of borehole electromagnetics (Zhou et al., 1987). In this study the problem of detecting a rectangular, sheet-like conductor missed by a drill hole was examined. The transmitter type used in the analysis was a downhole, grounded vertical electric dipole (GVED) operating at low frequencies. Detection was by means of a magnetic sensor in another borehole. The analysis showed that the technique is specific to steeply dipping fractures between the two boreholes. An advantage of the GVED source and a vertical magnetic field detector is that layered or horizontal features produce neither a primary nor secondary signal.

A study was made on the usefulness of 3-D gravity inversion for the delineation of conduits feeding a geothermal reservoir. Applying the analysis to data from the East Mesa geothermal field, Goldstein and Carle (1986) mapped linear to slightly arcuate zones of densified rocks. These correlate, in part, to the present-day circulation system identified by drilling and other geophysical data. Other parts of the densified zones are presumed to represent sealed and inactive segments of the system.

Long Valley Caldera Studies

LBL was authorized by DOE/GTD and DOE/BES to coordinate and expedite a year-long study to interpret and synthesize a large amount of geoscience data from the Long Valley Caldera in preparation for future scientific drilling that will serve the purposes of several federal agencies, DOE, USGS and NSF. Participating in the study were National Laboratories, the USGS, several universities and two private companies. A major symposium was held in March 1987 to present the results of the studies (Goldstein, 1987).

INDUSTRY REVIEW PANEL

In 1984 LBL began organizing meetings of an Industry Review Panel on Reservoir Technology, whose membership includes representatives from several commercial organizations (see Table 1). The last two meetings were held on April 24, 1986 and March 20, 1987. This industry group makes recommendations and comments on the relevance of the research being sponsored by DOE under the Reservoir and Brine Injection Technology and other GTD programs. These comments and suggestions are compiled by LBL and transmitted to DOE/GTD. Summaries and/or minutes of all five Panel meetings held to date can be obtained from the author.

TECHNOLOGY TRANSFER

An important part of the LBL program is the transfer of technology to the geothermal community. Over the last several years LBL scientists have presented lectures during various courses and workshops organized by the Geothermal Resources Council. The results of studies carried out under the program are published in scientific publications and open file reports, and are presented at technical meetings. LBL continues to make available to industry, universities and other national laboratories computer codes developed under the DOE Geothermal Program, and to advise geothermal companies in the application of advanced reservoir engineering and geophysical methods.

Table 1
Members of LBL's Industry Review Panel on Geothermal Reservoir Technology (March 1987)

Name	Organization
Mohinder S. Gulati (Chairman)	Unocal
Dick Benoit	Oxbow Geothermal Company
W.T. (Tom) Box	Geysers Geothermal Company
Louis E. Capuano, Jr.	ThermaSource Incorporated
John R. Counsil	Consultant
Steve Enedy	Northern California Power Agency
I.J. (Jerry) Epperson	Chevron Geothermal Co. of California
Thomas Hinrichs	Magma Power Company
Joe Iovenitti	Thermal Power Company
William F. Isherwood	Geothermex Incorporated
James Moore	California Energy Company
Walter Randall	GEO Operator Corporation
Ronald C. Schroeder	Berkeley Group Incorporated

ACKNOWLEDGMENTS

This review paper would not have been possible without the help of my LBL colleagues S.M. Benson, G.S. Bodvarsson, N.E. Goldstein and K. Pruess. This work was supported through U.S. Department of Energy Contract No. DE-AC03-76SF00098 by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal Technology.

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