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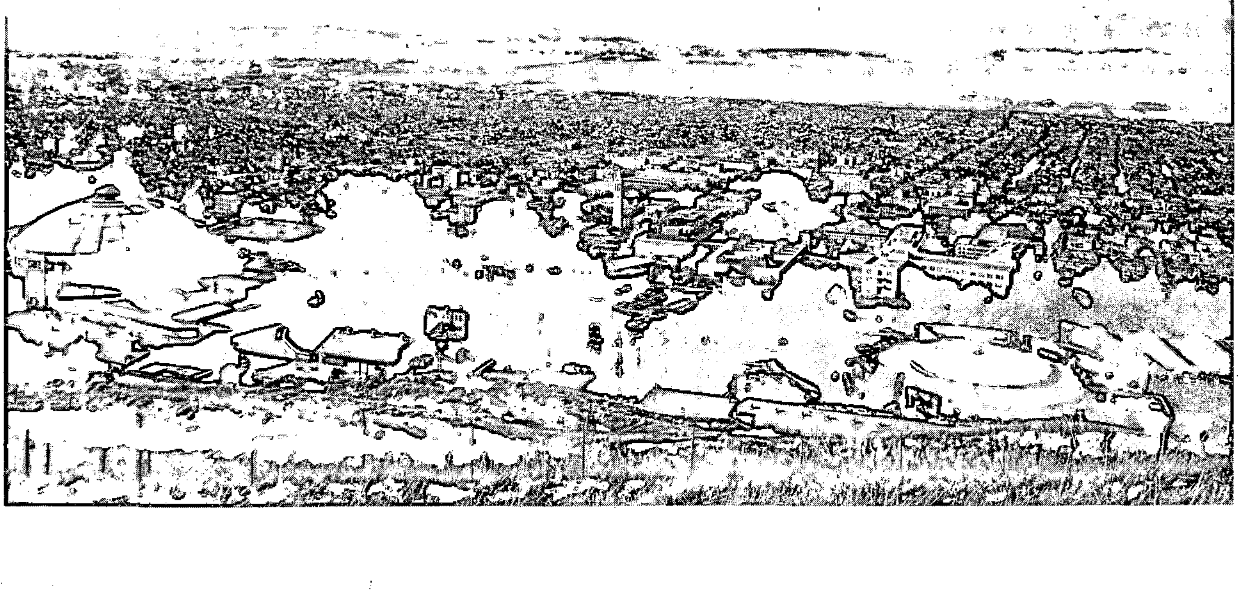

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Reservoir Technology Research at Lawrence Berkeley Laboratory

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ABSTRACT

The research being carried out at LBL as part of DOE/GTD's Reservoir Technology Program includes field, theoretical and modeling activities. The purpose 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 this work is to advance the state-of-the-art for characterizing geothermal reservoirs and evaluating their productive capacity and longevity under commercial exploitation. LBL's FY1986 accomplishments, FY1987 progress to date, and possible future activities under DOE's Reservoir Technology Program are discussed.

INTRODUCTION

The development and exploitation of a geothermal reservoir depends heavily on understanding its nature and establishing its properties. The overall hydrogeological characteristics of the system (e.g., lithology, structure, boundaries, fractured versus porous media, recharge) largely controls the circulation of the geothermal fluids under natural conditions and during exploitation. The thermodynamic and geochemical properties of the formation fluids and mineral assemblages will govern, in large part, the processes occurring in the reservoir; however the management of the energy resource (e.g., well locations and completions, rates of mass production and injection) is also an important factor controlling these processes, ultimately affecting the economic life of a geothermal field.

The goal of LBL's program in reservoir technology is to increase our understanding of reservoir characteristics, processes and behavior. The research being carried out includes theoretical, modeling and field activities, and is directed toward the development and validation of reservoir engineering and geophysical methodologies for characterizing and assessing hydrothermal resources.

PHYSICS AND CHEMISTRY OF FLUID EXTRACTION FROM GEOTHERMAL RESERVOIRS

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, laboratory and modeling studies are performed to evaluate the importance of different phenomena in geothermal systems. During FY1986 and FY1987 LBL has carried out a number of these studies. 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 were 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 heat transfer near the critical point.

Numerical simulation methods were 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.

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 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.

ANALYSIS OF PRODUCING GEOTHERMAL FIELDS

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 study of Klamaths Falls, Oregon), or by means of joint DOE/industry-sponsored projects (e.g., VSP and microseismic studies at The Geysers, 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, 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 Reservoir Technology 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 (Bodvarsson et al., 1986) developed under the DOE Geothermal Program.

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, 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.

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 delimitation 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 what had been suggested earlier, 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.

The Ellidaar and Seltjarnarnes fields are supplying geothermal fluids for the space heating system of 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 imminent encroachment of colder seawater into the reservoir.

A 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.

In cooperation with Italian researchers, a preliminary analysis of the permeability structure and fluid and heat flow conditions in the deeper horizons of the Lardarello system was completed (Pruess et al., 1987). 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 ($T > 300\,^\circ C$) 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.

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.

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 numerical analysis and field experiment.

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 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 8500 ft. 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 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 microearthquake (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 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.

In a related study over a producing part of The Geysers, O'Connell (1986), funded by DOE/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 concealed, sheet-like conductor missed by a drill hole was examined. The source was a downhole, grounded vertical electric dipole operating at low frequencies. Detection was by means of a magnetic sensor at the surface. The analysis showed that to detect this fracture zone the dipole moment of the transmitter has to exceed 100 ampere-meters.

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 original system.

DEVELOPMENT AND APPLICATION OF NEW 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 type of data needed to fully understand geothermal systems. The characteristics of this system were described by Benson (1986).

LBL's downhole sampler (Solbau et al., 1986) was successfully used in the Salton Sea Scientific Drilling Project well. On the first and only downhole run, a fluid sample was collected at a depth of about 10,000 ft, where the temperature was approximately 350 °C.

INDUSTRY REVIEW PANEL

The most recent meetings of LBL's Industry Review Panel on Reservoir Technology, whose membership includes representatives from several commercial organizations (see Table 1), were held on April 24, 1986 and March 20, 1987. The main purpose of these meetings is to review and comment on the activities being carried out under GTD's Reservoir and Brine Injection Technology Programs. This industry group makes recommendations and comments on the relevance of the research being sponsored by DOE under these and other GTD programs. These comments and suggestions are compiled by LBL and transmitted to DOE/GTD.

Following suggestions by the Panel, during FY1986 LBL organized and hosted the DOE/Industry Workshop on Geothermal Wellfield Measurements (Benson et al., 1985). Summaries and/or minutes of the Workshop and of all five Panel meetings held to date can be obtained from the author.

TECHNOLOGY TRANSFER

LBL scientists presented lectures during several courses and workshops organized by the Geothermal Resources Council. The results of studies carried out under the LBL reservoir technology program were published in scientific publications and open file reports, and were presented at technical meetings. LBL continues to make available to industry, universities and other national laboratories computer codes developed

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 Resources Company
Thomas Hinrichs	Magma Power Company
Joe Iovenitti	Thermal Power Company
William F. Isherwood	Geothermex Incorporated
James Moore	California Energy Company
Walter Randall	GEO Operator Company
Ronald C. Schroeder	Berkeley Group Incorporated

under the DOE Geothermal Program, and to advise geothermal companies in the application of advanced reservoir engineering and geophysical methods.

CONCLUDING REMARKS

During the remaining months of FY1987 LBL will continue its studies on: (1) characterization and mapping of reservoir parameters, processes and spatial dimensions; (2) monitoring and prediction of reservoir changes during production lifetime; (3) fracture detection and mapping; and (4) field case studies.

In FY1988 and beyond, LBL activities will be devoted to the following reservoir technology research areas that have a direct impact on the characterization and assessment of geothermal reservoirs, topics of fundamental importance to industry (schedules and milestones will depend on future funding levels):

(1) Development and testing of improved reservoir monitoring techniques to help characterize the effects of fluid recharge and pressure maintenance at producing geothermal fields.

(2) Development and testing of improved methods for determining fracture characteristics of geothermal reservoir rocks.

(3) Study of deep zones in hydrothermal convecting systems (the "roots" of geothermal reservoirs).

(4) Development of mathematical modeling capabilities for flow systems near and above the critical point of water.

(5) Development and incorporation into existing computer models of realistic descriptions of geothermal brines and rock-fluid interactions.

(6) Development and improvement of well testing and data analysis methodology to characterize and evaluate fractured two-phase reservoirs.

(7) Development of numerical models considering the interplay between the wellbore and the geothermal reservoir, especially in wells fed by multiple productive zones.

(8) Establishment of a "track record" of applications of advanced reservoir engineering and geophysical methodology to field problems.

(9) Upgrading of surface and downhole instrumentation for exploration and evaluation of geothermal reservoirs.

Joint DOE/industry projects, with the associated technology transfer activities, will continue to be one of the major thrusts of LBL's reservoir technology program.

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