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Author
Lippmann, M. J.

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GEOTHERMAL RESERVOIR TECHNOLOGY

M.J. Lippmann

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GEOTHERMAL RESERVOIR TECHNOLOGY

Marcelo J. Lippmann

Earth Sciences Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

ABSTRACT

A status report on Lawrence Berkeley Laboratory's Reservoir Technology projects under DOE's Hydrothermal Research Subprogram is presented. During FY1985 significant accomplishments were made in developing and evaluating methods for (1) describing geothermal systems and processes; (2) predicting reservoir changes; (3) mapping faults and fractures; and (4) field data analysis. In addition, LBL assisted DOE in establishing the research needs of the geothermal industry in the area of Reservoir Technology. These activities, as well as plans for FY 1986 are outlined.

INTRODUCTION

Significant advances in the understanding of the characteristics and behavior of geothermal reservoirs have been made over the last ten years. However, several important issues have yet to be resolved (Table 1). That is, we need to: (1) develop better methods for mapping and characterizing fractures in geothermal systems; (2) identify and quantify the phenomena controlling two-phase fluid flow in geothermal reservoirs; (3) evaluate the effects of noncondensible gases and dissolved solids in reservoir fluids on geothermal system behavior; (4) develop methods for analyzing enthalpy transients and two-phase well tests; (5) upgrade existing high-temperature downhole instrumentation; and (6) enhance and verify modeling techniques to predict capabilities and longevities of geothermal systems.

Accordingly, the purpose of Lawrence Berkeley Laboratory's (LBL) Geothermal Reservoir Technology Project, funded by the Department of Energy's (DOE) Geothermal Technology Division (GTD), has been to reduce uncertainties in predicting the productive capabilities and longevities of geothermal reservoirs by developing and verifying reliable and practical techniques for mapping reservoir parameters, for understanding and monitoring reservoir processes, and for modeling reservoir conditions before and during the exploitation stage.

This project involves the development of methodologies and instrumentation for: (1) characterizing and mapping reservoir parameters, processes, and spatial dimensions; (2) monitoring and predicting reservoir behavior during production; (3) fault and fracture mapping; and (4) surface and downhole measurements. The project includes field case studies in which developments are tested and vertified for transfer to industry. LBL is also identifying new research areas and providing general guidance to DOE as cognizant laboratory for its Geothermal Reservoir Technology Program.

DESCRIPTION OF MOST IMPORTANT FY1985 ACTIVITIES

Fracture detection and mapping. To summarize existing technology, a "White Paper" was published describing the state-of-the-art in the U.S. and assessing the research needs in this area (Goldstein, 1984). In addition, a one-day workshop for industry was hosted by LBL on July 11, 1985 to review DOE-supported fracture research activities. A summary report on the workshop was recently issued (Goldstein and Cox, 1985).

As far as research is concerned, a variety of numerical modeling, laboratory and field studies were carried out. Electromagnetic (EM) techniques for fracture detection and mapping are being evaluated by means of numerical modeling, laboratory experiments based on metal scale model analogs, and field surveys. Specifically, surface-to-borehole and cross-hole methods for detecting major conductors and hydraulic paths between wells are being studied.

Table 1.
Geothermal Reservoir Technology
Important Issues Yet To Be Resolved

- FRACTURES
    - Detection and Characterization
    - Fractures and Permeability
- TWO-PHASE FLOW
    - Relative Permeability Functions
    - Two-Phase Flow in Fractures (Deviation from Darcy's Law)
    - Capillary and Adsorption Effects
    - Two-Phase Flow in Wellbores (Coupling Between Wellbore and Reservoir through Multiple Feed Points)
- COMPOSITIONAL EFFECTS
    - Noncondensible Gases
    - Dissolved Solids
- RESERVOIR DIAGNOSTIC METHODS
    - Enthalpy Transients (Determination of Cold Water Fronts, Reservoir Properties, Natural Recharge, etc.)
    - Temporal and Spatial Variations in Concentrations of Noncondensible Gases and Dissolved Solids
- DOWNHOLE MEASUREMENTS
    - Upgrade of Downhole Instrumentation
- MODELING
    - Efficient Methods for Three-Dimensional Flow
    - Enhanced Capabilities for Front Tracking and Tracer Transport
    - Verification of Techniques by Applications to Field Data

In November 1984, a P- and S-wave vertical seismic profiling (VSP) survey was carried out at The Geysers in a joint project with Geothermal Resources International, Inc. The survey mapped (a) fracture density as function of depth, and (b) dominant fractured direction (Figure 1). The field data clearly show that shear wave velocity is highly sensitive to the density and orientation of fractures. Theoretical and laboratory work is being done to verify the field results, and it seems that the shear wave velocity ratios are related to several factors, including the dominant fracture direction relative to the S-wave displacement vector, the average spacing between fractures, and a function called fracture stiffness (Majer et. al., 1985).

During August 1985, LBL along with Seismographic Services Corp., Geophysical Services Corp., and Japan Metals and Chemical Corp. conducted a shear-wave VSP survey in a well at the Nigorikawa geothermal field in Hokkaido, Japan. There were two objectives: (1) to define a deep fracture zone (2000 to 2500 m depth) and its extent by utilizing reflected shear waves; and (2) to define the extent of a shallow (600 m) fracture zone using tomographic techniques. The data are now being processed at LBL's Center of Computational Seismology, with results of the tomographic study expected by early November 1985.

Analysis of Vapor-Dominated Systems. Pruess (1985) developed a quantitative model for the natural state and evolution of these systems. Computer simulations showed that upon heat recharge at the base, a single-phase liquid-dominated geothermal reservoir in fractured rock with low matrix permeability will evolve into a two-phase reservoir with boiling-point-for-depth pressure and temperature profiles. The study also indicated that a rather limited discharge event through cracks in the caprock, involving loss of only a few percent of fluids in place, is sufficient to set the system off to evolve into a vapor-dominated reservoir.

Various analyses of reservoir data from Lardarello, Italy, were performed by D'Amore and Pruess (1985), and Pruess et al. (1985). The key findings were: (1) most CO_2 in well discharges originates from mineral buffers; (2) released CO_2 equilibrates only partially with other gaseous constituents; and (3) long-term trends of vapor fraction support the three-source model of D'Amore and Truesdell (1979).

Bodvarsson and Witherspoon (1985) developed theoretical decline curves for vapor-dominated systems using a multiple-porosity technique (Pruess and Narasimhan, 1985). They studied the parameters controlling the flow rate decline, the effects of well spacing on steam recovery (Figure 2), and the applicability of P/z analysis to estimate reserves of vapor-dominated systems.

Relative Permeability Studies. Combined experimental and numerical studies of two-phase steam-water flow through porous media were carried out by Verma et al. (1985), yielding information on relative permeability functions and capillary pressure curves at temperatures up to 120 °C. The experimental setup is shown in Figure 3. The results indicated an enhancement of vapor relative permeability over that of non-wetting phases in two-component systems such as like oil and water, and gas and oil. It was hypothesized that this enhancement is the result of phase transformation effects at pore throats.

Analysis of data from different high-temperature (> 250 °C) geothermal fields shows that the sum of liquid and vapor relative permeability values is equal to unity for all saturations (e.g., Bodvarsson et al., 1985a).

Modeling Studies of Olkaria. A fully three-dimensional well-by-well model of the East Olkaria field in Kenya was developed (Bodvarsson et al., 1985a, b). This detailed model is the first of its type to be applied to a geothermal system. A

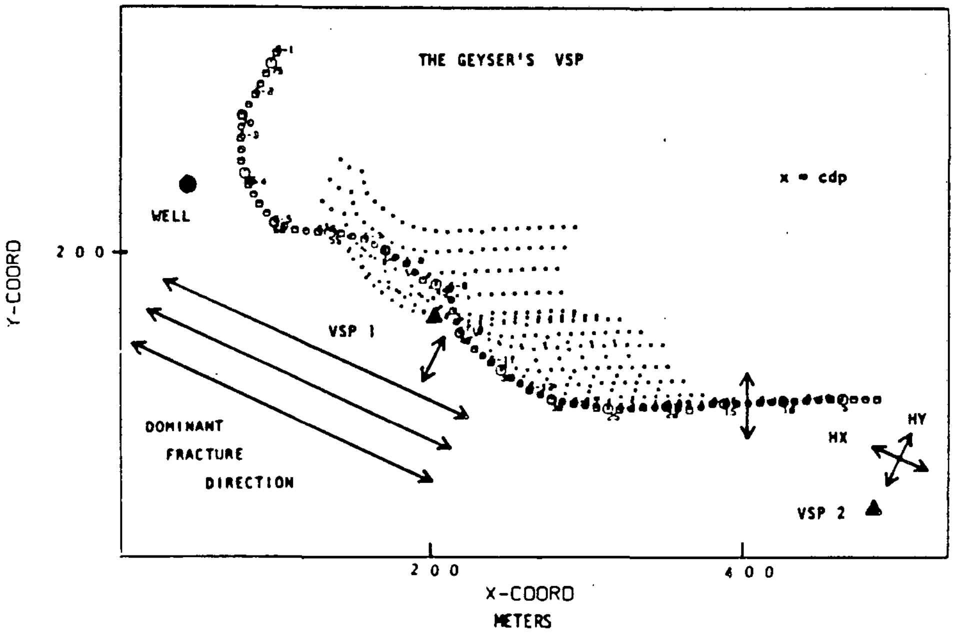

Figure 1. VSP survey layout at The Geysers. Triangles indicate vibrator positions; arrows indicate source polarization directions (Majer et al., 1985).

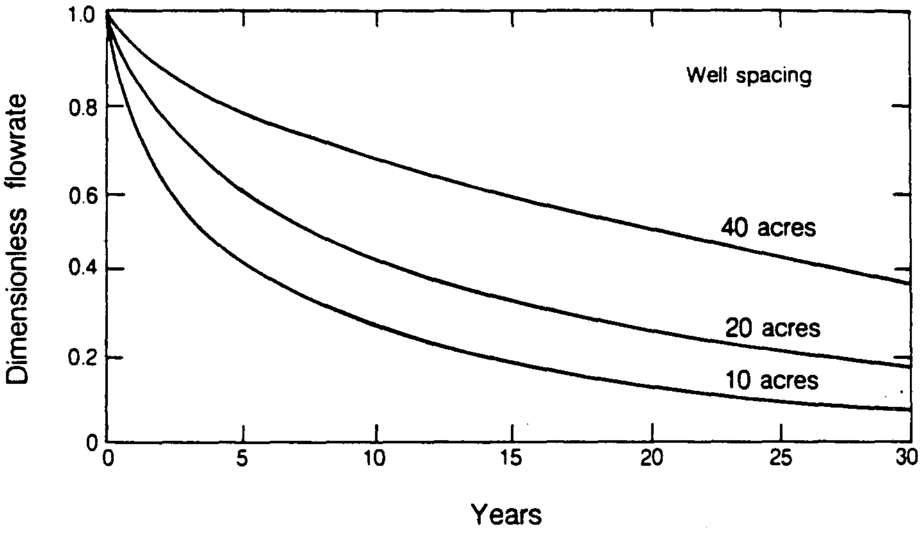

Figure 2. Effects of well spacing on flow rate decline in vapor-dominated fractured geothermal reservoirs (Bodvarsson and Witherspoon, 1985).

reasonable match with the flow rate and enthalpy history of all 25 production wells in the field was obtained. The model was used to determine the optimum well spacing, the overall generating capacity of the system, and the effect of brine reinjection on the behavior of individual wells and of the entire reservoir (Figure 4).

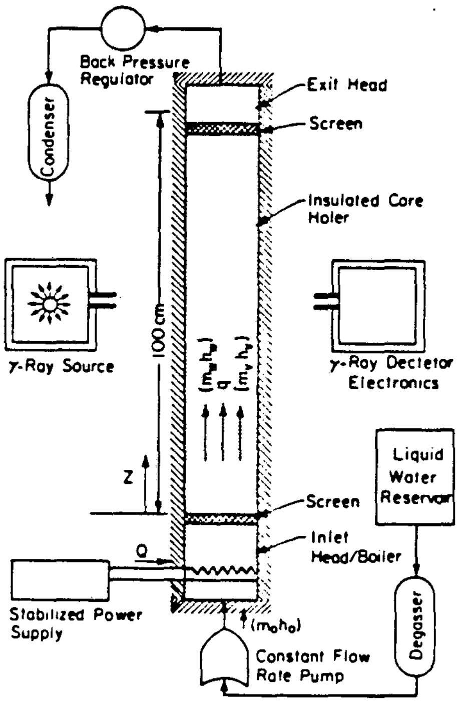

Figure 3. Schematic of the experimental setup to study two-phase steam/water flow in porous media (Verma et al., 1985).

Modeling Reservoir Changes at Cerro Prieto. During the period 1979-1983 repetitive high-precision dc resistivity measurements were made over the Cerro Prieto geothermal field at intervals of 6 to 24 months to study reservoir changes resulting from fluid production. This year Goldstein et al. (1985) performed two-dimensional iterative, least-square inversions of these data. The results of this analysis, supported by additional numerical experiments on artificial (simulated) data, have revealed that systematic, significant changes in resistivity have occurred within the Cerro Prieto area; e.g., (a) a slight increase in brine resistivity due to the recharge of cooler, less saline water from above and from the sides; (b) a possible slight reduction in bulk porosity due to calcite precipitation where cooler recharge waters come into contact with the hotter reservoir rocks; and (c) a slight two-phase condition around the production intervals.

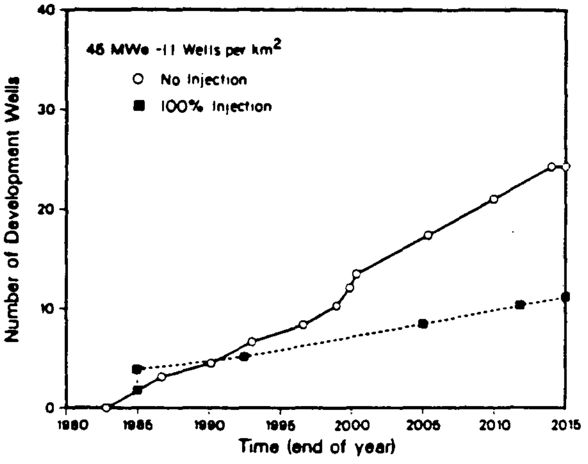

Figure 4. Effect of injection on the number of development wells needed to produce 45 MW_e at Olkaria using a density of 11 wells/km^2 (Bodvarsson et al., 1985b).

The study also showed that during 1981–1983 there was a reversal in the resistivity of the production region, which can be explained by the collapse of the two-phase region due to continued cooling of the reservoir. This hypothesis is supported by noted changes in the SiO_2 content of the produced brines as well as wellhead temperatures.

Hydrogeologic Model of Cerro Prieto. The hydrogeologic model of Cerro Prieto was updated based on data from recently completed wells. In the eastern region of the field a deeper reservoir (γ) was identifed at depths below 3100 m, that feeds a shallower reservoir (β) by fluid flow up a major normal fault (H) identified in earlier geologic studies (Halfman et al., 1985).

Enthalpy Transients in Two-Phase Geothermal Systems. A sensitivity study was carried out to determine the rock matrix and fracture parameters that control the enthalpy rise in fractured porous media under two-phase conditions (Lippmann and Bodvarsson, 1985). It was shown that the enthalpy transients are most sensitive to the characteristics of the relative permeability curves, matrix permeability and thermal conductivity, and fracture spacing and porosity. In contrast to porous media, in these fractured systems the effects of matrix porosity on enthalpy is small (Figure 5).

DOE-CFE Agreement on Geothermal Energy. LBL assisted DOE in the negotiations of a new three-year cooperative agreement with Comisión Federal de Electricidad (CFE). In February 1985 LBL organized a workshop between CFE and DOE-sponsored groups to review the latest data and results on the Cerro Prieto and Los Azufres fields, and to outline possible joint projects to be carried out under this agreement.

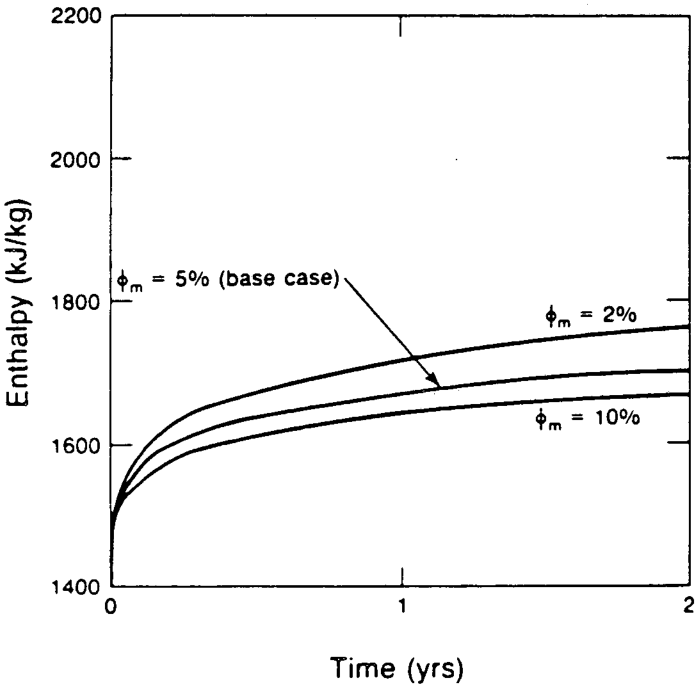

Figure 5. Effect of rock matrix porosity on flowing enthalpy transients in fractured two-phase geothermal systems (Lippmann and Bodvarsson, 1985).

Cognizant Laboratory Activities. As cognizant laboratory in Geothermal Reservoir Technology, LBL continued to assist DOE in formulating research plans for its Geothermal Reservoir Technology Program. To further determine the research needs of the geothermal industry and to review the appropriateness of DOE-funded projects to meet these needs, LBL organized and hosted on March 12, 1985 the second meeting of the Review Panel on Reservoir Technology (a third meeting is scheduled for September 30, 1985).

The results of the Panel meeting were reported to DOE for the consideration of GTD managers, and are available to the geothermal community (see Geothermal Resources Council Bulletin, July/August 1985, pp. 27–28).

PROPOSED PLANS FOR FY1986

An outline of LBL's FY1986 Geothermal Reservoir Technology activities as proposed to DOE is given below. The final program is being evaluated by GTD managers.

Subtask 1. Characterization and Mapping of Reservoir Parameters, Processes and Spatial Dimensions.

1A. Develop quantitative models of natural state and evolution of vapor-dominated geothermal reservoirs.

1B. Improve well testing techniques, especially for heterogeneous and fractured media systems.

1C. Explore applications of chemical data for reservoir diagnostics, using distributed-parameter models.

1D. Organize a joint industry-DOE/LBL workshop on instrumentation for wellhead and downhole measurements.

Subtask 2. Monitoring and Prediction of Reservoir Changes During the Production Lifetime.

2A. Demonstrate techniques for analyzing and predicting reservoir response to exploitation combining reservoir engineering, geophysical and chemical data.

2B. Study rock-fluid interactions and their impact on reservoir performance.

2C. Investigate effects of multiple feed zones on the behavior of geothermal wells.

Subtask 3. Improvement of Techniques for Modeling Reservoir Behavior.

3A. Develop capabilities for realistic modeling of brines and rock-fluid interactions at reservoir temperatures and pressures.

3B. Improve accuracy and efficiency of existing numerical codes.

Subtask 4. Fracture detection and mapping.

4A. Laboratory Studies.
  4A-1. Seismic-acoustic modeling.
  4A-2. Electromagnetic (EM) modeling.

4B. Numerical studies surface-borehole and cross-hole EM techniques.

- 4C. Field investigations.
  - 4C-1. Vertical seismic profile survey.
  - 4C-2. Electrical anisotropy.
  - 4C-3. Well log analysis.
  - 4C-4. Tectonics and fracture analysis.

Subtask 5. Laboratory Experiments.

- 5A. Perform and analyze laboratory experiments on "characteristic curves" (relative permeability and capillary pressure).

Subtask 6. Field Case Studies.

- 6A. Joint industry-LBL studies on U.S.fields.
- 6B. Analysis of Klamath Falls data.
- 6C. Field-demonstrate techniques developed under Subtasks 1 through 4.

Subtask 7. DOE-CFE Agreement.

- 7A. Assistance to DOE in technical coordination of the agreement.
- 7B. Delineation and descriptive studies of the Cerro Prieto and/or Los Azufres fields.
- 7C. Monitoring and modeling studies of the Cerro Prieto and Los Azufres fields.
- 7D. Data transfer between DOE and CFE.

Subtask 8. DOE-ENEL Agreement.

- 8A. Reservoir technology studies.

Subtask 9. Cascades Studies.

- 9A. Geophysical studies.
- 9B. Reservoir engineering studies.

Subtask 10. Cognizant Laboratory in Reservoir Technology.

- 10A. Assistance to DOE.
- 10B. LBL's Industry Review Panel.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720