CONF-890352--7

Proceedings of the

GEOTHERMAL PROGRAM REVIEW VII

"DOE Research and Development for the Geothermal Marketplace"

CONF-890352--
DE89 015627

March 21-23, 1989
San Francisco, CA

Coordinated by:

Meridian Corporation
Alexandria, VA 22302

Sponsored by:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Geothermal Technology Division
Washington, D.C. 20585

DISCLAIMER

Geothermal Field Case Studies that Document the Usefulness of Models in Predicting Reservoir and Well Behavior.

Marcelo J. Lippmann

Earth Sciences Division
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, California 94720

Abstract

The geothermal industry has shown significant interest in case histories that document field production histories and demonstrate the techniques which work best in the characterization and evaluation of geothermal systems. In response to this interest, LBL has devoted a significant part of its geothermal program to the compilation and analysis of data from U.S. and foreign fields (e.g., East Mesa, The Geysers, Susanville, and Long Valley in California; Klamath Fall in Oregon; Valles Caldera, New Mexico; Cerro Prieto and Los Azufres in Mexico; Krafla and Nesjavellir in Iceland; Larderello in Italy; Olkaria in Kenya). In each of these case studies we have been able to test and validate in the field, or against field data, the methodology and instrumentation developed under the Reservoir Technology Task of the DOE Geothermal Program, and to add to the understanding of the characteristics and processes occurring in geothermal reservoirs.

Case study results of the producing Cerro Prieto and Olkaria geothermal fields are discussed in this paper. These examples were chosen because they illustrate the value of conceptual and numerical models to predict changes in reservoir conditions, reservoir processes, and well performance that accompany field exploitation, as well as to reduce the costs associated with the development and exploitation of geothermal resources.

Introduction

Geothermal research at the Lawrence Berkeley Laboratory (LBL), which is mainly supported by the Reservoir Technology Task of the DOE Geothermal Program, is an integrated field, theoretical and laboratory program to develop techniques for characterizing and evaluating hydrothermal-geothermal systems. This special methodology is needed because the typical characteristics of geothermal systems (e.g. temperatures up to 350-400°C; presence of compositional, boiling and thermal fronts; general fractured nature of the reservoir rocks) tend to render inadequate the techniques and instrumentation used by the oil and gas industry, and by groundwater hydrologists.

The LBL program includes a geophysical component which concentrates on the development and testing of instrumentation, field techniques, and data processing and interpretation. Another part of the program is directed toward the development of well testing techniques, laboratory methods and mathematical tools for reservoir characterization and resource evaluation.

An important part of the geothermal activities at LBL is related to field case studies. Data from fields throughout the world are being gathered and analyzed. The main purpose of this effort is (1) to continue the field validation of techniques and instrumentation developed by LBL and other organizations; (2) to add to the understanding of the phenomena occurring in geothermal systems in their natural and exploited state; and (3) to transfer to U.S. industry, and the geothermal community in general, proven methodology and data on the characteristics of different geothermal systems and their response to exploitation.

Because of the need to acquire actual field data to test new technology and the significant interest shown by industry (e.g. Lawrence Berkeley Laboratory, 1988), LBL and other groups supported by DOE, have engaged in multidisciplinary studies of several U.S. and foreign geothermal fields. These studies are carried out under either formal or informal arrangements between DOE, the DOE contractors, and the field operators. In addition, the Geothermal Technology Organization, a DOE/industry organization set up to do cost-shared research, has recently begun sponsoring field projects (see for example Majer, 1989).

The general methodology utilized to study and to determine the future behavior of a hydrothermal system subject to different reservoir management plans was summarized in last year's Program Review (Lippmann, 1988). The purpose of this paper is to discuss the results of two field case histories and illustrate the usefulness of models in predicting the effects of exploitation on geothermal systems. One of the fields, Cerro Prieto, resides in predominantly porous sedimentary and low-grade metamorphic rocks, while the other, Olkaria, is found in fractured volcanic rocks. Many other geothermal systems have been studied, but these illustrate important aspects of the technology being developed under the DOE Geothermal Reservoir Technology Task.

Cerro Prieto, Baja California, Mexico

The Cerro Prieto field has been extensively studied by the Comisión Federal de Electricidad (CFE) of Mexico and by various DOE contractors and Mexican institutions participating in DOE/CFE cooperative agreements. More than 150 deep wells have been drilled in this area. Electricity production began in 1973; present installed capacity is 620 MWe. The exploration, development and changes resulting from the exploitation of this liquid-dominated system have been discussed in numerous papers and reports; recent summaries are given by Lippmann and Mañón (1987), Lippmann et al. (1989), and Truesdell et al. (1989).

Early studies of Cerro Prieto included the development of a conceptual model of the system, which indicated that fluid circulation is strongly controlled by faults and lithology. Under natural conditions, geothermal fluids enter the system from the east-southeast through a SE-dipping normal fault (Fault H) and tend to flow in a generally westward direction (Fig. 1). The important control of fault H on hot fluid recharge is evident by the high production rates that are observed in wells with open intervals intersecting, or near the fault zone.

Geochemical and reservoir engineering studies have established that under natural state conditions boiling in Cerro Prieto was restricted to an area in the west where geothermal fluids ascended through a sandy region, from about 1600 to about 1000 m depth, within an impermeable shale unit.

In response to production-induced drawdown, natural recharge by colder waters occurs, especially along the edges of the geothermal anomaly. The hydrogeological model that best describes this fluid movement was developed at LBL by Halfman et al. (1986) on the basis of geophysical, lithologic and temperature well logs, plus well completion data. This methodology is now being applied to other geothermal fields, including those in the Imperial Valley of southern California.

As a consequence of production, boiling has occurred in Cerro Prieto. In the shallowest reservoir (alpha reservoir) which is found between about 1000 and 1500 m depth and is restricted to the western region of the field, localized boiling occurs around some wells and influx of colder, less saline water is continually increasing. With time, the boiling zones tend to expand and stabilize. The cold recharge is from the west and through a normal fault (Fault L) that breaches the shale layer that overlies the reservoir. Some wells never develop a boiling zone because they occur near the natural recharge areas or in less exploited parts of the field.

In the deeper beta reservoir, which occurs between about 1500 and 2700 m depth and extends over the entire field, reservoir boiling is restricted to the upthrown block of Fault H (Fig. 2). This has resulted in significant mineral deposition in and around many of the wells, as indicated by fluid chemistry and by a progressive decrease in their flowrates. Contrary to what is observed in the alpha reservoir, boiling in the upthrown block of the beta reservoir is widespread and an extensive two-phase zone has developed. On the other hand, for wells completed in the downthrown block of Fault H, scaling occurs in the wellbore and/or wellhead separators, indicating that in this deeper block of the beta reservoir boiling is not yet extensive (Lippmann et al., 1989).

Schematic flow models for the entire Cerro Prieto field and for the beta reservoir have been developed (e.g., Fig. 3); the corresponding calculations of heat and mass flows through the system were made using the LBL code MULKOM (Pruess, 1988). The fluid recharge under natural conditions and the response of the system to exploitation, as well as the behavior of different areas of the field, were reproduced by these simple models. These models also help understand the processes occurring in the field, and explain the changes observed in wells completed in the various regions and reservoirs.

More sophisticated 3-D modeling efforts of Cerro Prieto, based on the methodology described by Bodvarsson et al. (1986) and Lippmann (1988) are underway. CFE and LBL engineers are applying the code MULKOM to simulate field behavior and to develop a reservoir management plan for this highly-productive system. Results of these modeling activities will be presented during the upcoming April 4-5, 1989 DOE/CFE symposium to be held in San Diego, CA.

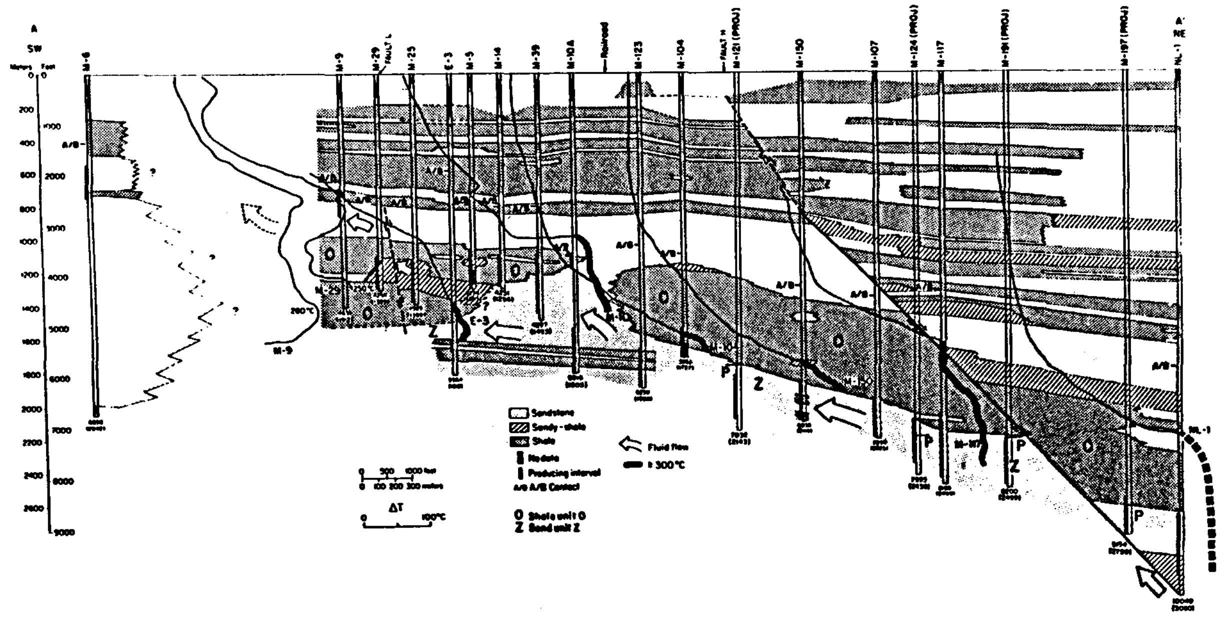


Figure 1. Southwest-northeast geologic cross section of the Cerro Prieto field showing schematically the lithology, and the flow of geothermal fluids (after Halfman et al., 1986).

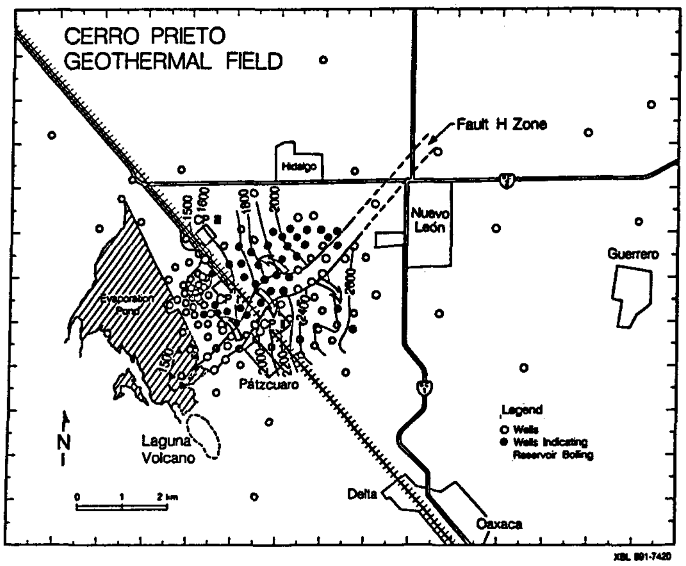


Figure 2. Location of Cerro Prieto wells indicating reservoir boiling and of the fault H zone. Depth (in meters) to the top of the Sand Unit Z (see Fig. 1). The arrows indicate the direction of geothermal fluid flow away from fault H. The fault zone is shown at the beta reservoir level (from Lippmann et al., 1989)

Olkaria East, Kenya

Electrical production in the Olkaria East geothermal field began in 1981; the present total installed capacity is 45 MWe. About 30 production wells have been completed in that part of the Olkaria field (Bodvarsson et al., 1989). The modeling effort has reached a high degree of sophistication, because, compared to Cerro Prieto, this field occupies a smaller area, has less wells and good quality field data.

The first numerical study of Olkaria was carried out in 1980, at a time when modeling was beginning to be accepted by the geothermal community as a useful tool for field evaluation. Additional studies followed in 1982 and 1984. In 1984 a detailed three-dimensional well-by-well model (Fig. 4) was developed for the Olkaria East field to determine the long-term electrical power production capacity of the system. The model was calibrated against the 1977-1983 flow rate and enthalpy histories of all existing wells, using porosities and permeabilities as adjustable parameters The study indicated that generation of 45 MWe was possible (Bodvarsson et al., 1987a and b); the code MULKOM was used in these calculations.

After the third 15 MWe power plant came on line in 1985, significant flow rates declines and enthalpy changes were observed in several wells. Production data for 1984-1987 were used to update the 1984 model. This new study facilitated the comparison between earlier predictions against observed data and evaluate the performance of that model (Bodvarsson et al., 1989).

In order to assess the accuracy of the 1984 model predictions, the recent well production histories were incorporated into the model and well performances were calculated. The computed enthalpies and mass flow rates were compared against the observed well data. One of the better matches is shown in Figure 5. For some wells, the model predictions matched the observed flow rates and enthalpies rather poorly. However, in spite of these differences the steam rate at the separator, an important parameter for estimating the electrical power that can be sustained by a well, was adequately predicted. For about 75% of the wells the predictions of produced steam rates and their decline with time were reasonably good (Bodvarsson, et al., 1989).

An additional way of testing the model was to independently estimate the contribution of the different zones feeding the wells, and compare to the model values. During the early stages of Olkaria model development, the fractional flow from each zone was estimated from geochemical data. Later, during the calibration process, the estimated contributions were modified to match the observed enthalpy transients. To evaluate the 1984 model, these contributions were compared to those computed by the LBL multiple feed zone wellbore model (Bjornsson and Bodvarsson, 1987) that uses well completion, wellhead, and downhole flowing pressure survey data as input. Figure 6 shows the result of one of these analyses. A generally good agreement was found between the relative contribution given by the 3-D model and the wellbore model for most wells (Bodvarsson, et al., 1989).

Even though the predicted performances of Olkaria wells were reasonably accurate, the 3-D model needed to be modified somewhat to improve the matches for about 25% of the wells. Little changes in permeability and productivity indices were required. The main adjustment was to increase the average porosity of the liquid-dominated zone underlying the steam zone from 2 to 4%. Bodvarsson et al. (1989) believe that this change is related to the use of a porous medium model to study a complex fractured system (further discussions of this issue are given in the referenced paper). They also found that the enthalpies of most wells are controlled by fluids recharging the wellfield. The higher porosity (4%) seemed to provide the proper enthalpy of the recharge fluids.

This simulation study on Olkaria East is one of the first, if not the first, in the open-file literature to document the inherent soundness of geothermal wellfield behavior predictions based on numerical models.

Impact of modeling studies on the cost of geothermal power

A significant cost of a geothermal project is associated with drilling exploration and development wells. Obviously, reservoir modeling studies cannot reduce the cost of equipment and materials used in this phase of a project. However, development of a conceptual model of a given geothermal system and numerical simulations studies to evaluate the effects of different production/injection well patterns and reservoir management plans become a very cost-effective tool once enough wells are completed and tested.

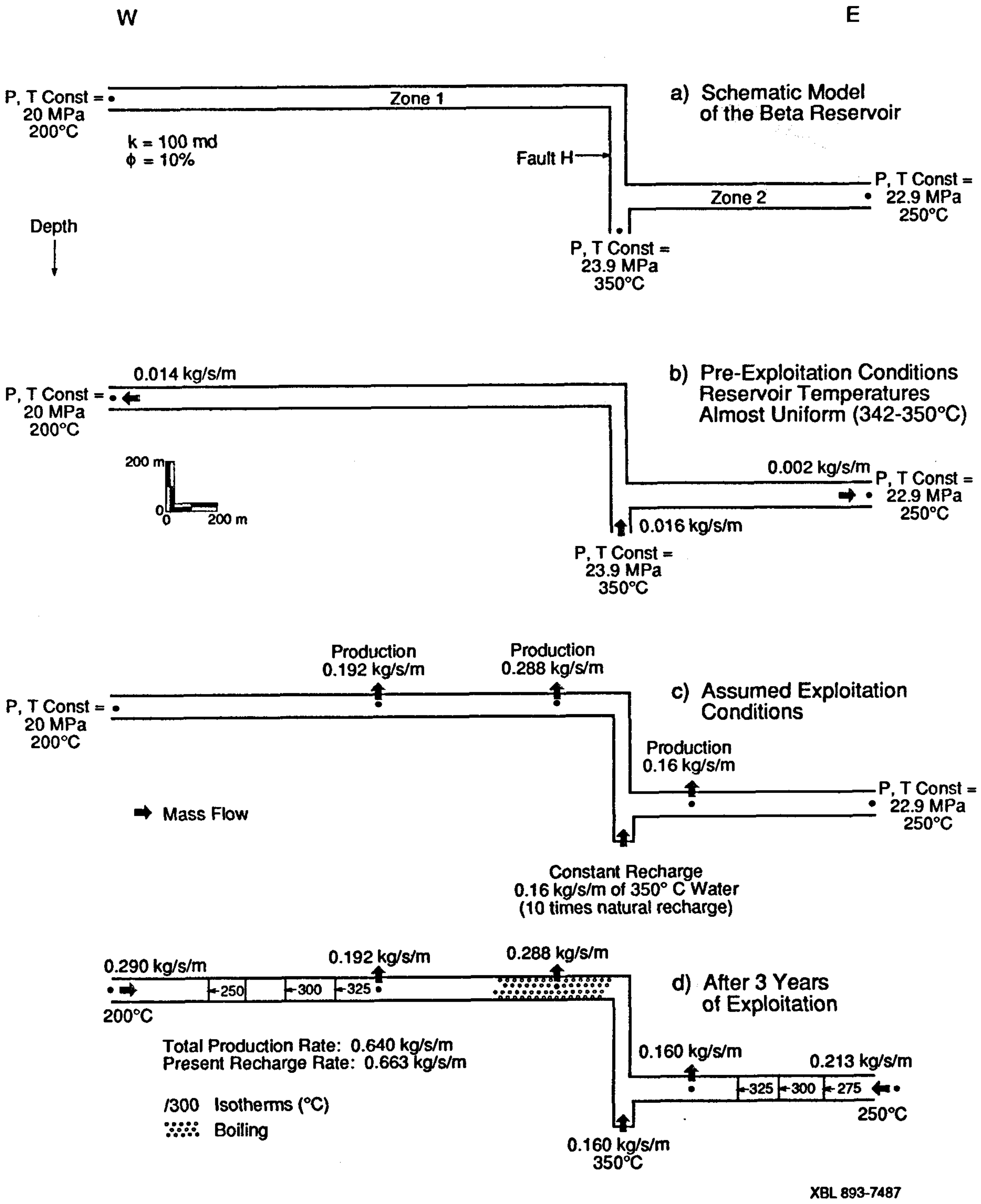


Figure 3. (a) Schematic vertical cross-sectional flow model of the Cerro Prieto beta reservoir system.
(b) Pre-exploitation (initial) flow and temperature conditions.
(c) Assumed exploitation regime.
(d) Temperature distribution, fluid flows and location of boiling zone after 3 years of production (from Lippmann et al., 1989).

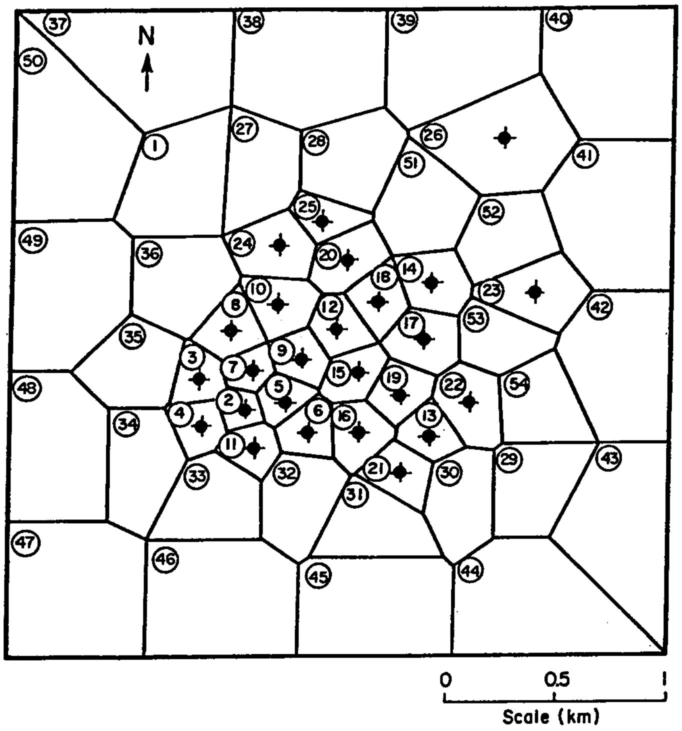


Figure 4. Plan view of the computational grid used in modeling the Olkaria East geothermal field (from Bodvarsson et al., 1987a).

The availability of a realistic conceptual model of a geothermal system helps the field developer/operator in targeting new exploration or development wells. By knowing the general location of the recharge and discharge areas, and approximate temperature distributions and depths of the reservoirs or main fluid-carrying fractures, the probability of drilling successful wells will be significantly increased. One will be able to locate and design the completion of new wells with more confidence. Reducing the number of dry/unproductive wells reduces significantly the overall cost of the project.

As is the case for oil, gas and groundwater systems, numerical simulation studies help in the design of reservoir management plans that maximize the total energy extracted from the resource and extend the commercial life of the field. In the case of Olkaria, Bodvarsson et al.(1987b) analyzed a number of reservoir development schemes to study (1) the effects of different well spacings/densities on well deliverabilities; (2) the total power production that could be sustained during a 30 year period; and (3) the impact of injection on well performance and reservoir depletion. For example, their study showed that injection would have a beneficial effect by sustaining the steam flow rates of the wells, thus reducing the number of make-up wells needed in the future. Just the money saved in drilling one less well, handsomely justifies the cost of a sophisticated simulation studies like the ones which were carried out to analyze the Olkaria East field.

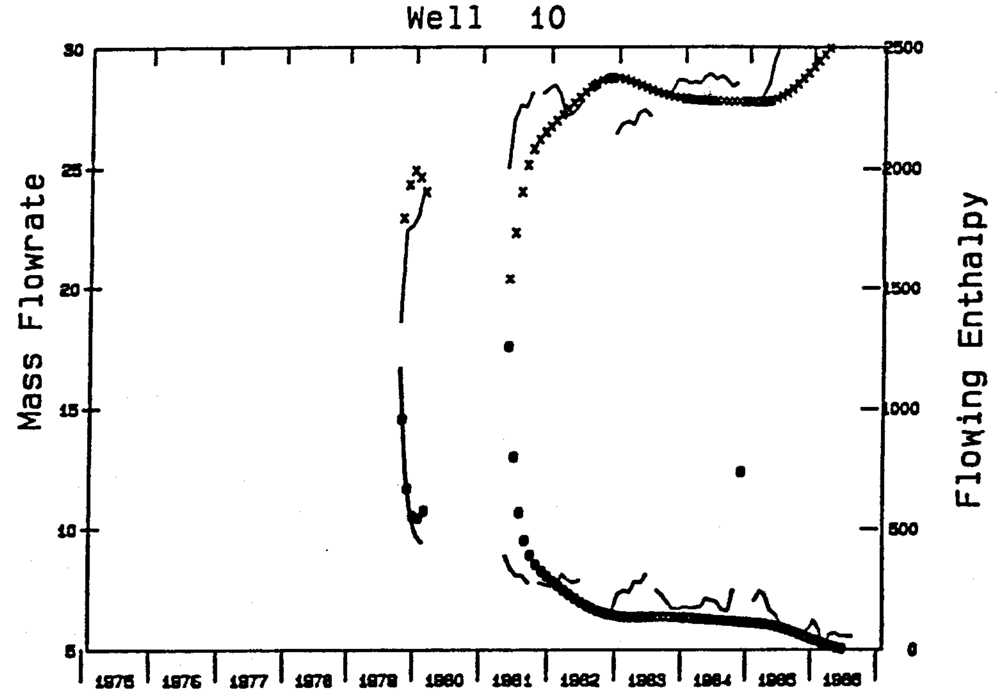
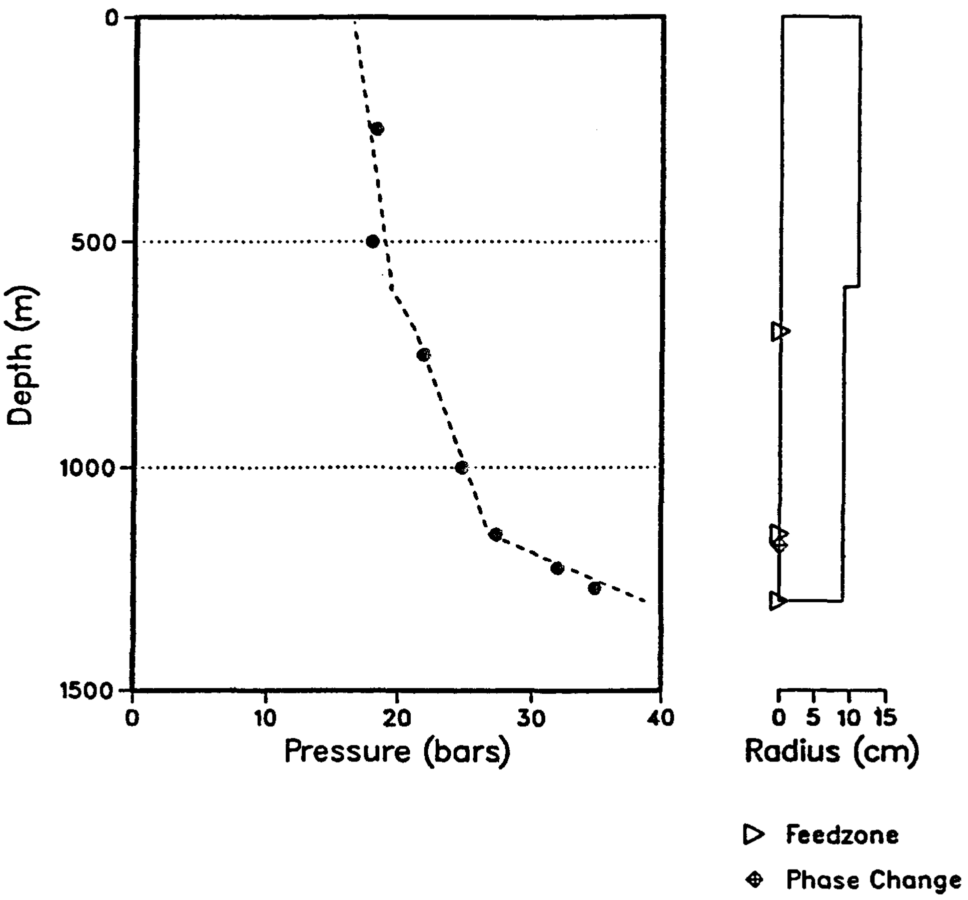


Figure 5. Comparison between predicted and observed 1984-1987 flowrates and enthalpies in Olkaria East well 10 (from Bodvarsson et al., 1989).



```
OLKARIA WELL OW-16
Pressure log during discharge. Measured 30-april-1981
Downhole pressures calculated for the following conditions.

     Wellhead pressure ( bar abs. ) :      16.50
     Wellhead temperature ( C )     :     202.86
     Wellhead dryness               :      0.817
     Wellhead enthalpy ( kJ/kg )    :    2440.00
     Wellhead total flow ( kg/s )   :      13.00

     Feedzone no:   Depth (m)   Flow (kg/s)   Enthalpy (kJ/kg)
     -------------------------------------------------------
          1           700.0       2.0000         2800.1
          2          1150.0      10.0000         2520.0
          3          1300.0       1.0000         1054.3
     -------------------------------------------------------
```

Figure 6. Analysis of flowing pressure survey of Olkaria East well 16 (from Bodvarsson et al., 1989).

Conclusions

To remain competitive the geothermal industry must reduce field development costs. As discussed by Pye (1989), one way is to shorten the time between investment and income, which can be achieved with an accelerated development program that relies on reservoir performance predictions. The experience being gained from testing and validating "in the field" existing and newly developed numerical models, will increase the confidence of industry (and investement groups) in the reliability of the results of numerical simulations studies required for planning the development and exploitation of a geothermal system.

The two case histories that have been discussed, illustrate our present capabilities in conceptual model development and numerical reservoir simulation as applied to geothermal systems. With the support of the DOE Geothermal Program, the methodologies have been advanced significantly during the last 10 years. However, improved capabilities are needed to model actual fractured geothermal reservoirs and to account for rock-fluid and fluid-fluid interactions in reservoirs subjected to production and injection. Research in the laboratory and in the field to increase our understanding of reservoir processes in hydrothermal reservoirs is also needed. Additional field case histories are required for continued testing and evaluation of the methodology, numerical models and instrumentation that are being developed.

In spite of the shortcomings that are still inherent in the existing methodology and technology, the geothermal industry has began using some of the approaches and models developed under the DOE Geothermal Reservoir Technology Task. As more individuals in industry become familiar with the research results of DOE-supported groups, the transfer of technology between these groups and the geothermal industry will be faster and more effective. Cooperative projects between DOE and industry, such as those funded by the Geothermal Technology Organization, have increased this technology transfer and the application of DOE-funded technology to hydrothermal systems under evaluation and/or exploitation.

Acknowledgement

Special thanks are due to Gudmundur S. Bodvarsson and Norman Goldstein of LBL for discussing and reviewing the manuscript. I want to acknowledge the assistance of Diana Parks and Ellen Klahn in producing the paper. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technologies, Division of Geothermal Energy of the U. S. Department of Energy under Contract DE-AC03-76SF00098.

References

Bjornsson, G. and Bodvarsson, G. S., 1987. A Multi-Feedzone Wellbore Simulator, *Geothermal Resources Council Trans., 11,* 503-507.

Bodvarsson, G. S., Pruess, K., Haukwa, C., and Ojiambo, S. B., 1989. Evaluation of Reservoir Model Predictions for the Olkaria East Geothermal Field, Kenya, paper presented at the 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 24-26, 1989 (also submitted to *Geothermics).*

Bodvarsson, G. S., Pruess, K., and Lippmann, M. J., 1986. Modeling of Geothermal Systems, *Journal Petrol. Tech., 38,* 10, 1007-1021.

Bodvarsson, G. S., Pruess, K., Stefansson, V., Bjornsson, S. and Ojiambo, S. B., 1987a. East Olkaria Geothermal Field, Kenya, 1. History Match with Production and Pressure Decline Data, *J. Geophys. Res., 92,* B1, 521-539.

Bodvarsson, G. S., Pruess, K., Stefansson, V., Bjornsson, S. and Ojiambo, S. B., 1987b. East Olkaria Geothermal Field, Kenya, 2. Performance Predictions of Well Performance and Reservoir Depletion, *J. Geophys. Res., 92,* B1, 541-554.

Halfman, S. E., Mañón, A., and Lippmann, M. J., 1986. Update of the Hydrogeologic Model of the Cerro Prieto Field Based on Recent Well Log Data, *Geothermal Resources Council Trans., 10,* 369-375.

Lawrence Berkeley Laboratory, 1988. Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology-Research in Progress, Berkeley, CA, June 14-15, 1988, Report LBL-25635, 141 p.

Lippmann, M. J., 1988. Reducing Long-Term Reservoir Performance Uncertainty, Proc. DOE Geothermal Program Review VI, San Francisco, CA, April 19-21, 1988, Conf.-880477, 39-43.

Lippmann, M. J. and Mañón, A., 1987. The Cerro Prieto Geothermal Field, *Geothermal Science and Technology, 1,* 1-38.

Lippmann, M. J., Truesdell, A. H., Mañón M., A., and Halfman, S. E., 1989. The Hydrogeologic-Geochemical Model of Cerro Prieto Revisited, paper presented at the 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 24-26, 1989.

Majer, E. L, 1989. GTO-DOE/Industry Cost Shared Research: Microseismic Characterization and Monitoring in Geothermal Systems, this volume.

Pruess, K., 1988. SHAFT, MULKOM and TOUGH: A Set of Numerical Simulators for Multiphase Fluid and Heat Flow, *Geotermia, Rev. Mex. de Geoenergía, 4,* 1, 185-202.

Pye, S., 1989. Research Can Keep Geothermal Competitive, paper presented at the 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, January 24-26, 1989.

Truesdell, A. H., et al., 1989. The Response of the Cerro Prieto Reservoir to Exploitation as Indicated by Fluid Geochemistry, paper to be presented at the April 4-5, 1989, Symposium on Cooperative Geothermal Research of the United States and Mexico, San Diego, CA.