Title
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Publication Date
1988-04-01

LBL-25245

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EARTH SCIENCES DIVISION

Presented at the U.S. Department of Energy Geothermal
Program Review VI, "Beyond Goals and Objectives,"
San Francisco, CA, April 19–21, 1988

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April 1988

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

REDUCING LONG-TERM RESERVOIR PERFORMANCE UNCERTAINTY

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ABSTRACT

Reservoir performance is one of the key issues that have to be addressed before going ahead with the development of a geothermal field. In order to select the type and size of the power plant and design other surface installations, it is necessary to know the characteristics of the production wells and of the produced fluids, and to predict the changes over a 10-30 year period. This is not a straightforward task, as in most cases the calculations have to be made on the basis of data collected before significant fluid volumes have been extracted from the reservoir.

The paper describes the methodology used in predicting the long-term performance of hydrothermal systems, as well as DOE/GTD-sponsored research aimed at reducing the uncertainties associated with these predictions.

INTRODUCTION

One of the main objectives of the research and development activities supported by the DOE Geothermal Program is to contribute to the reduction of the cost of electricity generated from hydrothermal resources. As described by the Impacts of Geothermal Research Model (IM-GEO; Traeger et al., 1988) one of the four major cost components of a hydrothermal energy project is related to resource analysis, that is, the effort to find and define a resource.

Resource analysis includes the evaluation of the reservoir. This paper discusses the general approach for predicting reservoir behavior, and the research being done under the DOE Hydrothermal Research Program toward reducing long-term reservoir performance uncertainties. The work described is part of a coordinated research program carried out primarily by Idaho National Engineering Laboratory (INEL), Lawrence Berkeley Laboratory (LBL), Lawrence Livermore National Laboratory (LLNL), Stanford University, and University of Utah Research Institute (UURI).

BACKGROUND

In evaluating geothermal systems one has to keep in mind their complex and dynamic nature. Even in their natural state, before fluid production begins, these systems show continuous mass (fluids and chemical species) transport and (conductive and convective) heat transfer (Donaldson et al., 1983). Other important physical processes active in geothermal reservoirs include phase changes (boiling and condensation), dissolution and precipitation of minerals, and stress changes caused by pore-pressure changes. Most of these processes are coupled. For example, phase changes disturb chemical equilibria, often resulting in precipitation/dissolution of minerals that could then alter porosities and permeabilities of the reservoir rocks. This could in turn, affect the mass transport in the system (Bodvarsson et al., 1986).

Considering that each geothermal system tends to have individual characteristics, it is difficult, even dangerous, to apply a universal evaluation strategy. Because of the complexity of the systems and the coupling between different reservoir processes, one has to rely on modeling studies to be able to respond to questions such as:

(1) What is the generating potential of the system?
(2) How fast will the production wells decline?
(3) How will the average enthalpy and chemistry of the produced fluids change with time?
(4) What are the effects of injection on well production and long-term reservoir performance?
(5) Where should the production and injection wells be located in order to optimize the exploitation of the field?

These questions must be answered to establish whether the development of a given hydrothermal system will be economically attractive. During the discovery or exploratory phase of a project, questions about field performance can only be addressed with a significant degree of uncertainty, since very little reservoir and well performance data are available. Even later, during the acceptance stage of a project when extensive well testing occurs (Drenick, 1988), no exact answers can be given; generally there is still a lack of long-term (> 1 year) performance information. Thus, initially the reservoir engineer will tend to give conservative estimates that might later be revised as additional data become available.

Conservative estimates could make a project uneconomical or result in the selection of a small and less-efficient power plant. However, these constrained estimates could reduce the risk of constructing surface installations that eventually may become inefficient due to lack of fluid reserves, low well deliverabilities, or changes in fluid characteristics.

Under DOE's Geothermal Program, the methodology for evaluating hydrothermal systems is continuously improving. However, one has to remember that the reliability of long-term predictions of reservoir performance will have to be based on the availability of a sufficient volume of quality field data (i.e., the quality of the predictions will never exceed that of the data).

METHODOLOGY FOR EVALUATING HYDROTHERMAL SYSTEMS

The reservoir engineer addresses the problem of predicting the future behavior of a geothermal system by characterizing it through the analysis of all available information, by carrying out and interpreting well tests, and by performing simulation studies. A pivotal part of this approach is the development of a conceptual model representing the up-to-date knowledge of the system and its dynamics (Bodvarsson et al., 1986). The model should identify (1) the main recharge and discharge areas; (2) the lithology and geologic structures that control the movement of fluids in the subsurface; and (3) the most relevant processes active in the system and where they possibly occur.

After a plausible and coherent model of the system has been developed, it is necessary to choose a mathematical model that can realistically simulate and correctly compute the performance of the reservoir and wells. There are various methods to model these behaviors, applicable at different stages of a geothermal project; from simple curve-fitting techniques to complex distributed-parameter numerical models. The choice of method depends on the amount and type of data available, and on the specific issues the model is supposed to address (Bodvarsson et al., 1986).

The first step in the evaluation of a geothermal system is to model the natural state. Very valuable insight into the characteristics of the system can be learned from natural state modeling. For example, information can be gained on formation permeabilities, boundary conditions for fluid and mass flow, and the thermodynamic state of the fluids throughout the system. The initial simulation work must be based on the conceptual model developed earlier and should quantify (or constrain) some of the reservoir parameters. By modeling the natural state one will obtain a consistent set of initial and boundary conditions for the next step in evaluating a geothermal system, the exploitation modeling study (Bodvarsson et al., 1986.)

The prediction of long-term performance of a given field, that is, the estimation of its total generating capacity, well rate decline and changes in produced fluid characteristics, and the evaluation of alternative reservoir management plans, has to be based on an exploitation model. The model incorporates all relevant field information, such as reservoir properties (permeabilities and porosities), thermodynamic state of the system (distributions of pressure, temperature, phase saturation and chemical characteristics), and data on field exploitation history (transient flow rate, enthalpy, chemical characteristics and reservoir pressure). In many cases the available data set is incomplete (or of poor quality), requiring sensitivity studies of the most important parameters.

Various types of exploitation models exist with different capabilities for answering long-term performance questions. These are the lumped-parameter and the distributed-parameter models; the latter ones can either simulate a lumped wellfield or individual wells. Well-by-well models are more detailed, and can address most questions related to future reservoir and well performance, and evaluate different production/injection scenarios. If the geothermal system is very complex, a three-dimensional model may be required. The development of such models, especially the calibration against all available well data, could represent significant costs in manpower and computational expenses (Bodvarsson et al., 1986).

Independent of the sophistication of the available methods, one should always start with the simplest possible model that can explain the field data. The final complexity of the modeling effort should be determined by the performance issues that need to be resolved and by the quantity and quality of the available data (Bodvarsson et al., 1986).

The basic methodology to compute the future behavior of geothermal systems is presently available; the requirements for carrying out these predictive calculations and the general approach to follow are given in Table 1 and Figure 1. What are generally missing are long-term production data that can be used to (1) confirm the conceptual, natural state and exploitation models developed for different fields, and (2) validate the methodology used to evaluate their long-term performance under production. It is clear that there is a need for field-case studies documenting the experience gained at different geothermal areas. However, one should remember that many geothermal fields have been under development for less than 10 years and the data are not generally in the public domain.

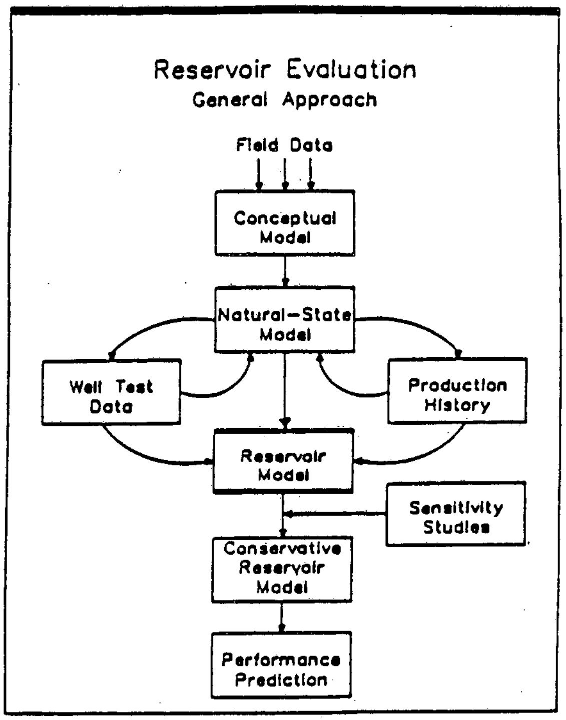

Figure 1. General approach to geothermal reservoir evaluation (from Bodvarsson, 1987)

TABLE 1

STEPS FOR PREDICTING THE LONG-TERM PERFORMANCE OF HYDROTHERMAL SYSTEMS

DATA COLLECTION

- Use available (or develop new/improved) tools, instrumentation and methodologies to collect geological, geophysical, geochemical and reservoir engineering data, before and after fluid production begins
- Carry out theoretical studies and laboratory experiments to identify fundamental reservoir processes and parameters

ANALYSIS AND INTERPRETATION OF AVAILABLE DATA

- Use available (or develop new/improved) methodologies to analyze and interpret field and laboratory data
- Determine rock and fluid properties
- Establish the distribution of pressure, temperature, chemical species and thermodynamic conditions in the system, and their changes with time
- Locate and characterize reservoir boundaries
- Evaluate well production/injection characteristics and their changes with time
- Identify the most important reservoir processes, before and after field exploitation began
- Develop a conceptual model of the system

MODELING RESERVOIR BEHAVIOR

- Apply available (or develop new/improved) modeling techniques to create a natural state model of the system
- Apply available (or develop new/improved) modeling techniques to create an exploitation model of the system
- Carry out sensitivity studies on important reservoir parameters
- Evaluate different reservoir management strategies to optimize long-term field performance.
- (Develop and document field case history to validate methodologies and models used to study and evaluate hydrothermal systems.)

THE DOE HYDROTHERMAL RESEARCH PROGRAM

Over the recent years, under DOE sponsorship, significant advances have been made in understanding reservoir processes/phenomena, and in the areas of well testing (methods, tools, and data analysis) and modeling techniques to simulate the flow of heat, fluids and chemical species in porous and/or fractured reservoirs. However, there is still a lack of quantitative information on important processes and parameters that control the flow of steam-water mixtures in fractured and porous reservoirs (e.g., relative permeability curves). Still to be clarified is the temporal relation between tracer (chemical) and thermal breakthroughs, taking into consideration the complexity of the fractured/porous network in the reservoir. Uncertainties exist in some important aspects of reservoir dynamics, especially with regard to chemically and mechanically coupled processes, and fluid and heat flow processes in the deeper zones of geothermal systems. There is also a need for field case studies documenting the validity of long-term reservoir performance predictions that may require the re-evaluation of the original assumptions made to reach these predictions.

The field, laboratory and theoretical activities (listed below) being carried out under the Hydrothermal Research Program are contributing to the reduction of uncertainties in establishing the long-term performance of geothermal systems. This research is intended to (1) increase the availability and quality of field data, (2) improve the data analysis and modeling techniques, and (3) add to our understanding of reservoir processes, important elements for predicting reservoir performance. A significant part of this work is sponsored by joint DOE/industry projects.

Recent and ongoing activities under the Hydrothermal Research Program

Based on the recognition of the importance of field case studies (see above), a significant effort of DOE's Hydrothermal Research Program has been directed towards field projects, a number of them in cooperation with industry.

Geologic and geochemical methods to analyze and interpret data from cuttings, cores and fluid samples have been developed and applied to a number of geothermal areas to establish the properties of these systems and prevailing conditions (e.g., Stallard et al., 1987; Moore and Adams, 1988; Nielson and Wright, 1988).

State-of-the-art geophysical techniques to determine geologic structures and the characteristics of fractures in the reservoir have been developed and applied to several geothermal areas (e.g., Salton Sea, East Mesa and The Geysers, California). They are discussed in detail by Zhou et al. (1987), Kasameyer (1988), Nielson and Wright (1988) and Goldstein (1988).

New well testing techniques, including tracer tests and tracer compounds, and their application to different geothermal areas (such as Los Azufres, Mexico), are discussed by Adams et al. (1986) and Horne (1988).

The development of a new interpretation method for injection test data has allowed determination of the increase in near-bore permeabilities in Los Azufres wells, which are completed in fractured volcanic rocks (Benson et al., 1987). Under the existing DOE/CFE agreement on geothermal energy, additional information is being obtained and analyzed to identify the process causing permeability enhancement that results from cold water injection (possibly thermal contraction and fracturing of the rock mass bounding the natural fractures).

The construction of an improved version of the LBL downhole sampler (Solbau et al., 1987) has been completed. The new tool can capture a 2-liter fluid sample at bottomhole temperatures of up to 350°C.

Models have been developed to (a) simulate the behavior of wells fed by more than one producing zone (Bjornsson and Bodvarsson, 1987; Ripperda and Bodvarsson, 1988); (b) analyze wellbore heat transmission in layered reservoirs (Wu and Pruess, 1988); (c) consider the effects of non-condensible gases and gravity on reservoir performance (Gaulke and Bodvarsson, 1987; Bodvarsson et al., 1988; McKibbin and Pruess, 1988); (d) study temperature regimes near the critical point of water (Cox et al., 1988); and (e) evaluate the response of fractured geothermal systems (Pruess and Wu, 1988; Renner, 1988). The new and existing modeling capabilities have allowed the study of the relative importance of given reservoir processes (e.g., boiling/condensation, compositional effects, deep recharge), the heat and mass transfer in wellbores, and the effects of fractures on reservoir performance.

Laboratory studies of heat and mass transfer in fractured hydrothermal reservoirs have been carried out at INEL (Renner, 1988), Stanford (Horne, 1988) and are underway at LBL. The purpose of LBL's studies is to determine the relative permeability curves for steam-liquid water mixtures in fractures with rough surfaces.

The multidisciplinary studies of the Cerro Prieto and Los Azufres fields in Mexico continues under the DOE/CFE agreement. The results of the 1986-1989 activities will be presented during a conference planned for April 1989. The Salton Sea Scientific Drilling Program is still active (DOE, 1988); a well test is being planned for the near future.

The study of the geology and geochemistry of the Valles caldera, New Mexico, continues. The DOE-sponsored work is focused toward the hydrothermal alteration and the fracture characteristics in the hydrothermal system (e.g. Hulen et al., 1987). DOE and Oxbow Geothermal are planning a tracer test in Dixie Valley, Nevada, to determine the characteristics of the subsurface fracture network.

The ongoing study of hydrothermal alteration and fluid inclusions in the Coso, California, system is part of a DOE/UURI/California Energy Co. project (Echols et al., 1986). GEO and DOE/LBL have recently completed a self-potential survey of East Mesa, California, in a repeat of a 1978 survey. Under a similar cooperative effort, preliminary plans for a series of well and tracer tests have been developed.

A long-term geochemical fluid sampling program is underway at Heber, California, as part of a DOE/UURI/Chevron project. At The Geysers, California, DOE/LBL, Unocal and Geysers Geothermal Co. have just began cooperating on high-frequency seismic monitoring of fluid injection; this became the first project funded by the recently-created Geothermal Technology Organization.

SUMMARY

The above-mentioned geothermal areas are just some in which data are being gathered to test and validate the instrumentation and methodology developed as part of DOE's Program. Independent of formal joint projects, the DOE-sponsored groups continue to collect and analyze information from different hydrothermal fields. The exchange of data is usually done on a personal basis between researchers having common research interests. Long term performance data have been gathered on several fields abroad, including Wairakei, New Zealand; Lardarello, Italy; Cerro Prieto and Los Azufres, Mexico; and Krafla and Svartsengi, Iceland. Additional, but shorter, open-file case histories are becoming available on many foreign and some U.S. fields.

The theoretical and laboratory work, as well as the experience gained in collecting and analyzing field case study data, are helping to determine the important processes active in hydrothermal systems, and to validate simulation models that can now be used with increasing confidence to predict long-term reservoir performances.

ACKNOWLEDGMENTS

Special thanks are extended to Karsten Pruess for his comments and suggestions. I am grateful to Mary Bodvarsson and Leslie Fairbanks for their help in producing this paper. The 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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