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RESERVOIR TECHNOLOGY RESEARCH AT THE IDAHO NATIONAL ENGINEERING LABORATORY

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ABSTRACT

The Idaho National Engineering Laboratory (INEL) has been conducting geothermal reservoir research and testing sponsored by the U.S. Department of Energy (DOE) since 1983. The INEL research program is primarily aimed at the development of reservoir engineering techniques for fractured geothermal reservoirs. Numerical methods have been developed which allow the simulation of fluid flow and heat transfer in complex fractured reservoirs. Sensitivity studies have illustrated the importance of incorporating the influence of fractures in reservoir simulations. Related efforts include fracture characterization, geochemical reaction kinetics and field testing.

INTRODUCTION

The objective of reservoir technology research programs at the Idaho National Engineering Laboratory (INEL) is to develop analytical and interpretive methods to more effectively develop and utilize hydrothermal resources. The goals of this research, which is funded primarily by the U.S. Department of Energy Geothermal Technology Division, are to reduce the adverse thermal and chemical effects of injection on geothermal reservoirs, to improve predictions of reservoir performance during exploitation, to provide for more effective production and injection well location, and to verify new techniques for evaluating geothermal reservoirs in young volcanic terrains.

The major portion of the research currently being conducted by INEL focuses on understanding fluid flow and fluid migration in fractured reservoirs. Methods have been developed to predict the fate of injected fluids and to improve field testing and data interpretation procedures for application to geothermal reservoirs in which fractures are significant features. These analytical methods are not restricted to fracture flow, but can be applied to dual permeability reservoirs which have both matrix and fracture permeability.

Related activities include the characterization of fracture systems, the development of methods to simulate rock-water chemical interactions in geothermal systems, and industry-cooperative field testing and reservoir analysis. During fiscal year 1987, INEL assisted DOE in the establishment of the Geothermal Technology Organization, whose mission is complementary to that of the Geothermal Drilling Organization. This paper summarizes the status of these research activities.

FLUID MIGRATION IN GEOTHERMAL RESERVOIRS

Injection of geothermal fluids is considered one of the primary reservoir concerns facing geothermal developers. Injection is required in almost all geothermal fields for fluid disposal, and may also be used to offset reservoir depletion, to improve heat extraction and to reduce the risk of subsidence. However, injection can cause early thermal breakthrough with a consequent reduction in enthalpy and may result in loss of injectivity due to chemical interactions in the reservoir. Selection of production and injection well locations depends on effectively balancing the positive and negative effects of injection.

Fractures are significant features in most geothermal reservoirs (even those reservoirs with primarily matrix permeability). They can represent high-mobility channels for the migration of injected fluids through geothermal reservoirs. Horne (1982) has documented loss of production due to thermal interference in several geothermal fields and has demonstrated that injected fluids can move rapidly through fractures.

Heat transfer in a geothermal reservoir is a function, in part, of the thermal conductivity of the rock, the surface area contacted by the fluids, the temperature gradient and the fluid mass flux (Horne, et al, 1987). A few large fractures may be the primary controlling factors in fluid flow in a reservoir. However, secondary fractures and a

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permeable matrix can represent a much greater surface area for heat transfer and rock-water chemical interactions. A realistic interpretation of fluid migration and thermal breakthrough must account for reservoir complexity.

Complex Reservoir Simulation

Standard reservoir engineering techniques which are based on homogeneous media are inadequate to assess the migration of injected fluids in fractured geothermal reservoirs. Recent work at INEL on the nature of flow and tracers through fractured media have made simulation of complexly-fractured reservoir feasible. The INEL simulation techniques incorporate two significant features, dual-permeability and fluid front tracking. The dual permeability model, FRACSL, allows simulation of pressure, flow and heat transfer in fracture systems and/or permeable reservoir matrix. A particle tracking algorithm allows the fluid or chemical front to be tracked in a reservoir, as well as the pressure front.

Modeling of fractured media has been based on two primary approaches, continuum and discrete. The continuum approach is based on a lumped parameter model of the fracture system. The scale of the model must be large enough so that the fractured rock can be treated as if it were homogeneous. The discrete approach represents the opposite end of the spectrum. All fractures which are considered relevant are modeled as individual entities. Presently, discrete fracture simulations are limited to reservoirs with few relevant fractures or to small portions of a fracture system.

INEL's reservoir simulation takes a slightly different approach. The FRACSL simulation code can be used to simulate transient and steady-state flow in a fractured, permeable media. The smaller fractures and the permeable matrix are simulated as permeable matrix cells, while larger fractures are represented as discrete elements (Clemo and Hull, 1986). FRACSL computes fracture and matrix flows using a common head distribution and allows advective interchange of fluid between fractures and the matrix. The code employs a particle tracking routine in which individual fluid particles are tracked through the reservoir. This enables explicit simulation of heat transfer and chemical interactions at the fluid/rock interface.

The FRACSL code has been verified against analytical solutions for flow and transport in porous media and in single fractures (Clemo and Hull, 1986). Laboratory models have been used to validate flow and transport algorithms in fracture systems and fractured permeable media. While the physical models used in the laboratory studies cannot realistically represent a full-scale geothermal reservoir, they have been useful for confirming that the code accurately simulates those physical processes which control fluid movement in a geothermal reservoir. Because all physical parameters of the models can be defined or measured, no fudge factors can be used to make the simulated data match the measured data. As a consequence, errors in the code are immediately apparent.

The most complex laboratory model used to validate the code was a dual-permeability model incorporating a series of interconnected fractures in a permeable matrix. Figure 1 presents a comparison of the actual fluid migration through this "reservoir" to that predicted by the code. The studies demonstrated that, while the pressure response to injection may be well-defined, pressure data were not sufficient to analyze actual fluid movement in the reservoir. More detailed discussions of these laboratory studies are presented in Hull and Koslow (1986), Hull and Clemo (1987) and Hull, et al (in press).

Work is continuing at INEL on an innovative approach to dealing with complex fractured reservoirs. A method employing representative elements has been developed which will allow simulation of reservoirs that are too large for discrete simulation, yet are dominated by a few major fractures, making the continuum representation impossible.

An important milestone in the FY-88 INEL program is the publication of the FRACSL code for use by industry. Current efforts are aimed at streamlining the code so that effective reservoir-scale simulations can be made The code is run on a Cyber 176 at INEL, but modifications in progress will enable the code to be run on a work-station type computer (4 megabyte capacity). The modified code will use sparse matrix numerics instead of the proprietary ACSL driver. Heat transfer simulation using a particle-based routine similar to the fluid particle tracking routine will simplify thermal simulations.

An algorithm which greatly simplifies the simulation of fluid transport along fractures and the advective and diffusive movement of fluid between fractures and the matrix is scheduled to be completed this fiscal year. The basis for the approach to simulation of fluid transport in fractures is the superposition of random dispersion and diffusion upon deterministic advection. Under some circumstances, this approach is inaccurate and inefficient. A more accurate and efficient routine, based on probability density functions sampled in Monte Carlo fashion, has been developed to simulate the interaction of fluid and tracer with the matrix when diffusion is dominant.

Significance of Fractures to Fluid Migration and Heat Transfer

The dual-permeability code has been used to assess the sensitivity of fluid migration and thermal breakthrough forecasts to simplifying assumptions commonly used in simulations of geothermal reservoirs. The studies were based on a production and injection well in a fractured, liquid-dominated reservoir. The wells were spaced 1200 m apart, with a 90-m injection interval. The reservoir consists of a permeable matrix with 22 fractures, some of which are encountered by both wells.

Fluid migration and thermal breakthrough for this reservoir were compared to simulations of hydraulically-equivalent reservoirs in which only a single fracture is simulated or in which the fractures are replaced by an equivalent porous media representation. The studies demonstrated that simulating a few of the dominant fractures is all that is required to analyze the pressure response to production and injection in the reservoir (Hull and Clemo, 1987, Hull and Clemo, in press).

However, simplifying the reservoir in order to run reservoir-scale simulations can yield significant error when assessing heat transfer and the potential for thermal breakthrough. Figure 2 shows the extent of the cooling front in the reservoir after 2000 days of injection. An equivalent porous media simulation of this reservoir would have predicted that the cooling front would have moved only about 100 meters away from the injection well. On the other hand, a simulation based on a single fracture connection between the wells would have predicted that the cooling front would have reached the production well in less than 2000 days (Figure 3).

Porous media approximations can greatly overestimate the time to thermal breakthrough in fractured geothermal reservoirs. Decisions to locate injection wells based on these results could limit power generation due to a premature decline in production well enthalpy. (Studies by Lawrence Berkeley Laboratory have shown that this reduction in enthalpy is partially counteracted by improved mass flow from the production wells in some reservoirs (Calore, et al, 1986)).

On the other extreme, assuming a single fracture connection between the injection and production wells may not be a substantial improvement. Well placement decisions based on these assumptions would be conservative, perhaps unreasonably so. INEL's studies have shown that a more realistic representation combining matrix and fracture flow in a fractured geothermal reservoir can provide a more reasonable basis for forecasting thermal breakthrough, resulting in more efficient heat extraction and reservoir development.

Fracture Characterization Studies

A determination of fracture characteristics is important for proper modelling of flow through fractures. The most direct measurement of fracture characteristics in geothermal systems can be made in existing, well-explored geothermal systems. At the present time, researchers have published very little of this information. INEL researchers are evaluating other geologic systems, including fossil geothermal systems and hydrothermal ore deposits, which are likely to be analogous to active geothermal systems.

INEL's present work focuses on the Cascade volcanic region and will be performed in conjunction with geologic characterizations being done at the University of Utah Research Institute. While this region has been relatively unexplored in the past, recent deep corehole drilling has provided an extensive geologic data base which can be correlated with data from similar geologic environments. The characterization studies currently in progress are evaluating not only the physical characteristics of fractures, but also the effect of resource depth on the nature of the fracture systems. Regional structural data will be reviewed to determine if fracture systems can be generalized in geologic regions such as the Cascades. The study will be correlated with fracture fluid flow studies to provide a basis for determining the significance of fracture inhomogeneities to exploration and resource development.

Plans for Future Research and Field Tests

Future research at INEL is aimed at additional sensitivity studies of fluid migration and heat transfer based on fracture location and reservoir parameters. The assumptions which form the basis for current heat sweep models will be evaluated. Kinetics-based geochemical relationships will be incorporated in fluid transport codes to evaluate rock-water interactions in the reservoir. The development of more streamlined and cost-effective reservoir simulation techniques will continue. Expansion of the FRACSL code's capability for three-dimensional reservoir simulation (Miller and Allman, 1986, 1987) will continue.

As reservoir analysis techniques are developed, field testing to verify application of these analytical techniques is planned. INEL is currently cooperating with other DOE-funded laboratories and universities and GEO Operator Corporation in a comprehensive field study of production and injection at East Mesa. A series of field tests in conjunction with a long-term flow test of the Salton Sea Deep Hole has been planned and approved by DOE. Negotiations are currently in progress with other developers to enable field verification of new reservoir techniques in fractured, high-temperature hydrothermal reservoirs.

GEOTHERMAL TECHNOLOGY ORGANIZATION

In addition to cooperative field tests of technology developed in the DOE research program, DOE seeks a more formalized procedure for conducting cost-shared research with the geothermal industry. INEL assisted the industry and DOE in the formation of the Geothermal Technology Organization (GTO) and in preparation of an agreement to fund cost-shared research. The GTO was formed to complement the Geothermal Drilling Organization and has a specific charter to sponsor research projects which have a high probability of yielding short-term benefits in the areas of reservoir performance and energy conversion technology. The charter for the organization was adopted on April 15, 1987. DOE has allocated funds to assist in sponsoring research projects which are selected by the GTO. The first research project should be selected during the final quarter of 1987.

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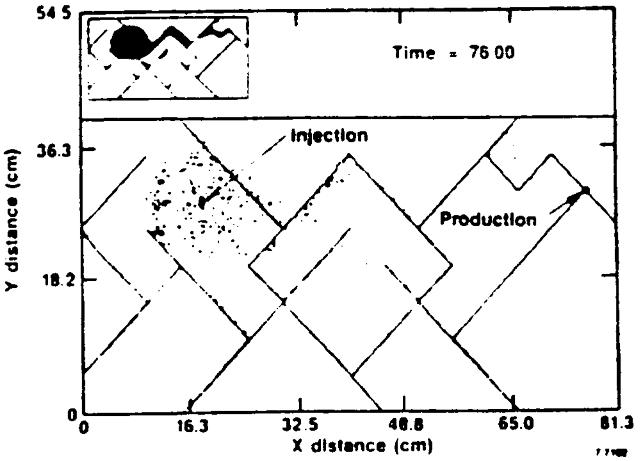

Figure 1.
Comparison of fluid migration in dual-permeability laboratory model (upper left) to simulations using FRACSL.

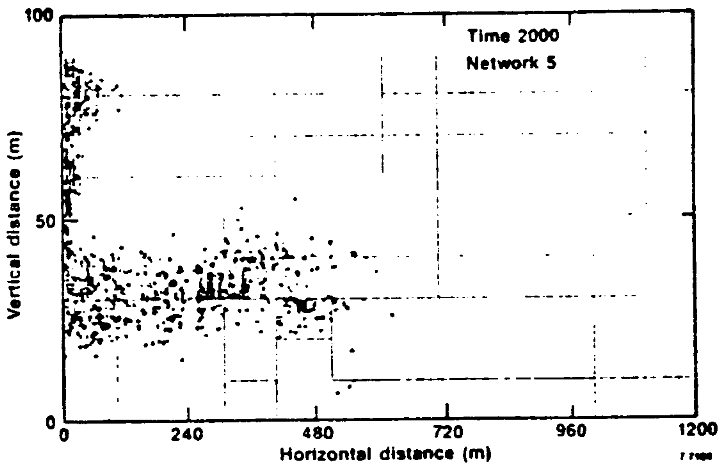

Figure 2.
Extent of cooling between injection well (left) and production well (right) in a fractured reservoir after 2000 days of injection.

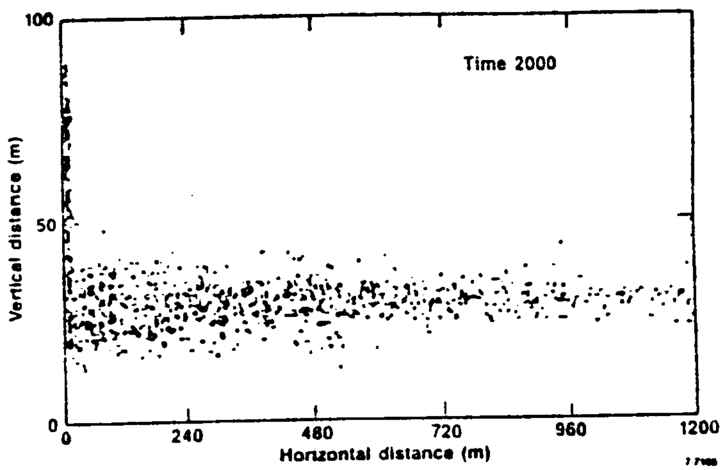

Figure 3.
Predicted extent of cooling between injection well (left) and production well (right) after 2000 days of injection, based on assuming a single fracture connection between the injection and production wells.

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