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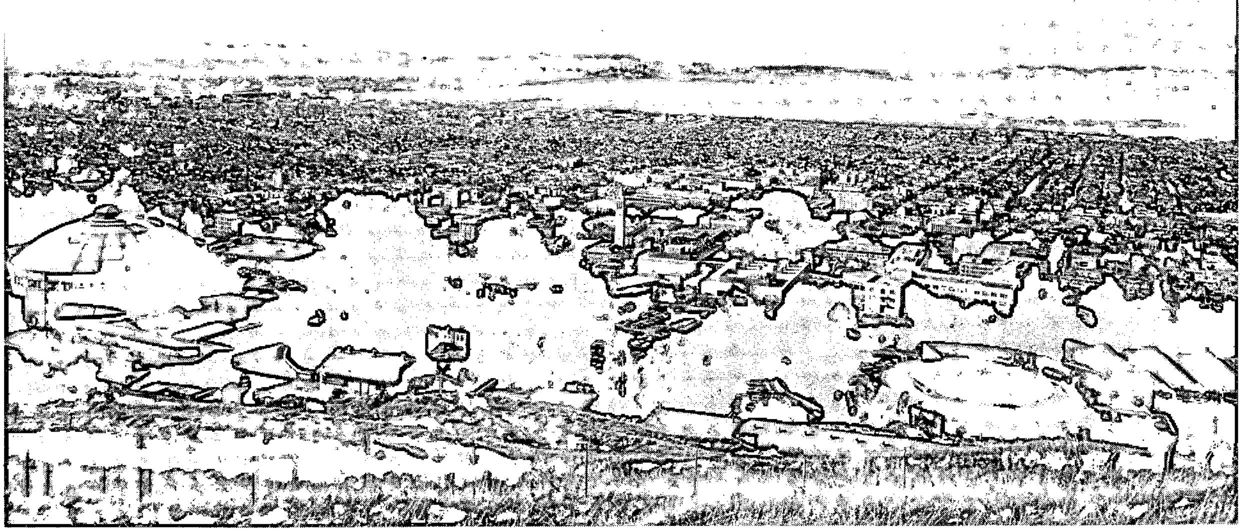

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Modeling of Geothermal Reservoirs: Fundamental Processes, Computer Simulation, and Field Applications

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ABSTRACT

This article attempts to critically evaluate the present state of the art of geothermal reservoir simulation. Methodological aspects of geothermal reservoir modeling are briefly reviewed, with special emphasis on flow in fractured media. Then we examine applications of numerical simulation to studies of reservoir dynamics, well test design and analysis, and modeling of specific fields. Tangible impacts of reservoir simulation technology on geothermal energy development are pointed out. We conclude with considerations on possible future developments in the mathematical modeling of geothermal fields.

INTRODUCTION

Any scheme to harness the natural heat of the Earth for useful purposes is based on some kind of model about the nature, distribution, and availability of a specific geothermal resource. Models are developed from qualitative and quantitative information gathered during the exploration phase of a project, and they can take on different form, depending on the detail of available observational data, the nature of the questions posed by the project under consideration, and the personal or collective bias of the researcher(s). In its simplest form, the model of a geothermal prospect may encompass little more than some rough ideas about approximate depth and areal extent of the reservoir, and about reservoir temperature and permeability. As more data are assembled through geologic, geochemical, and geophysical observation, through exploratory drilling, and through well tests, it becomes possible to identify the thermal and hydrologic structure of the reservoir with more confidence and detail. Specific mathematical models can then be constructed to evaluate and optimize geothermal utilization schemes. Mathematical models may range in complexity from a simple accounting of total heat and fluid reserves, such as "stored heat" calculations, all the way to models which describe fluid and heat flow conditions in a geothermal field with great spatial and temporal detail, based on a mathematical description of the fundamental physical and chemical processes in the reservoir. Spatially detailed, or "distributed parameter" models, involve large amounts of numerical work, requiring special computer programs known as "reservoir simulators" for their construction.

Beginning in the early to mid-seventies, considerable efforts were made to develop capabilities for computer simulation of the behavior of geothermal systems. The proponents of this development hoped that numerical reservoir simulators would improve our understanding of geothermal reservoirs, both in their natural state and in response to fluid production and injection, and would thereby contribute to more rapid and efficient resource utilization. However, in the early days there was much skepticism in the geothermal community about the feasibility and potential benefits of reservoir simulation. Many people questioned whether a realistic and useful numerical simulation capability could in fact be achieved. In addition, there were intense controversies about the proper mathematical and numerical methodologies to be used for describing fluid and heat flows with phase change effects. An important milestone in the development and acceptance of geothermal reservoir simulators was reached in 1980 when a code comparison project demonstrated satisfactory agreement between several simulation programs for a number of multiphase fluid and heat flow problems (Stanford, 1980). Over the last ten years the field of geothermal reservoir simulation has matured considerably, and has developed from an esoteric and controversial subject into a technique widely applied in routine engineering practice.

An early review of geothermal reservoir simulation methodology and applications was given by Pinder (1979). Recent overviews of the field with extensive bibliography are those by O'Sullivan (1985) and Bodvarsson et al. (1986). The present article is not intended as a review, but as an attempt to critically evaluate the state of the art of geothermal reservoir simulation. We discuss aspects of mathematical and numerical methods, as well as applications of these methods to the simulation of generic and "real" geothermal reservoirs, and of laboratory experiments. The two basic questions that we are concerned with are: How "good" is the available simulation technology, i.e., what is it that our computer software tools are able to provide? And what have we learned from applications of the simulators, both in terms of improved understanding of geothermal reservoir dynamics, and in terms of improved engineering of geothermal energy projects?

SIMULATION METHODOLOGY

Early work on numerical modeling of geothermal reservoirs emphasized the development of appropriate methodology. The basic physical processes governing fluid and heat flow were clarified, and a mathematical description of these processes was developed. The governing equations take the form of coupled partial differential or integral equations, which describe the variation of temperature, pressure, and other thermodynamic parameters as functions of continuous space and time coordinates. For numerical solution the continuum equations need to be discretized. This has been accomplished with different approaches, including finite differences, integral finite differences, and finite elements. Discretization results in a set of nonlinear coupled algebraic equations, which can be solved by approximate linearization or by iterative procedures. Nonlinearities arising in phase change are so severe that only iterative methods provide satisfactory solution. Whether approximate linearization or iteration is employed, most of the computational work done by a numerical simulator is expended in solving large systems of linear equations. Standard linear algebra methods have been employed in geothermal reservoir simulation, including direct solution and iterative matrix techniques.

We have developed a general-purpose reservoir simulator "MULKOM" which implements special techniques for effectively dealing with nonisothermal multiphase flow (Pruess, 1983, 1988). The basic governing equations solved by MULKOM describe mass and energy conservation for multicomponent fluids which in addition to water may contain a non-condensible gas such as CO_2 and dissolved solids such as NaCl or SiO_2. Fluid flow is described with a multiphase extension of Darcy's law; in addition there can also be binary diffusion in the gas phase. Heat flow occurs by conduction and convection, the latter including sensible as well as latent heat effects. Conversion of compressible work into heat, and heat exchange between fluids and rocks, are also modeled. The description of thermodynamic conditions is based on the assumption of local thermodynamic equilibrium among all phases (liquid, vapor, solid). Fluid properties are represented by steam table equations for water, and by suitable empirical correlations for other constituents. Different components (H_2O, CO_2, SiO_2,...) can be present in several phases, according to local phase equilibria or by way of kinetic rates. Special techniques are used to handle phase transitions. All thermophysical and hydrologic parameters (including porosity and permeability) which appear in the governing equations can be arbitrary (nonlinear and differentiable) functions of the primary thermodynamic variables.

In the early days of geothermal reservoir simulation many different approaches were pursued by different investigators (Pinder, 1979). However, over time there seems to have occurred a general convergence of methods, and the simulators presently in use share most of the basic characteristics. We feel that at the time of this writing issues of simulation methodology have been largely settled. A number of reservoir simulation codes are available in the public domain as well as from private vendors, which can handle highly nonlinear fluid and heat flow processes, including phase transitions, in a robust and stable manner. The accuracy of these codes has been demonstrated by comparison with analytical solutions, as well as by applications to laboratory and field data. Limitations still exist in modeling chemically and mechanically coupled processes, in which formation porosities and permeabilities can vary in response to mineral dissolution and precipitation, and changes in pore pressure and rock stress. Also there is a lack of empirical data on multiphase flow properties of real rough-walled fractures. Further work is needed to improve our ability to model sharp phase and concentration fronts.

For completeness it should be mentioned that numerical reservoir simulation is widely used in the oil and gas industry, and in the management of groundwater resources (Peaceman, 1977; Aziz and Settari, 1979). Geothermal reservoir simulation borrows heavily from concepts and methods developed in these fields.

APPROACHES FOR SIMULATING FLOW IN FRACTURED MEDIA

Some special problems are posed by the fact that most geothermal reservoirs occur in fractured formations with low rock matrix permeability. The fractures provide most of the reservoir permeability, while most of the fluid and heat reserves are stored in the matrix. From a conceptual viewpoint the simplest approach for modeling flow in fractured media is to explicitly include fractures in the flow domain by means of suitably chosen small volume elements (grid blocks). Because of the amount of geometric detail involved in this approach, it can only deal with highly idealized problems with very few fractures and a high degree of symmetry. At the opposite extreme compared to the "explicit fractures" approach is the "effective continuum" technique (Pruess et al., 1985a). This approach involves the drastic simplification of not making any geometric representation of the fractures at all; instead their flow effects are approximated by means of suitably modified hydrologic parameters, chiefly relative permeability curves. Thereby the numerical problem is reduced to that of a porous medium model; however, such a "porous medium" or "effective continuum" approximation can only be justified when matrix and fractures remain in approximate thermodynamic equilibrium locally at all times (Pruess et al., 1988).

For geothermal reservoirs with spacing between major fractures often as large as several tens of meters, the thermodynamic equilibration between matrix and fractures in response to changing conditions in the fractures (caused by fluid withdrawal or nonisothermal reinjection) is a slow process. Indeed, thermal diffusivity of rocks is typically of the order of 10^{-6} m^2/s, so that penetration of conductive effects into matrix blocks with linear dimension of 30 m will require approximately 30 years. As far as fluid flow is concerned the permeability contrast between fractures and matrix is typically of the order of 10^4 (10 millidarcy versus 1 microdarcy); the corresponding contrast in hydraulic diffusivities is even larger because of small fracture porosity. Thus, reservoir perturbations induced by production or injection operations will propagate through the fracture system typically more than 100 times faster than through the rock matrix. These considerations indicate that one should expect persistent nonequilibrium conditions between matrix and fractures in many fractured geothermal reservoirs during exploitation. An effective continuum approximation should be applicable only when fracture spacing is "sufficiently" small. For conductive equilibration with impermeable blocks to occur within a few months, fracture spacing must be less than 2 - 3 m. If one wishes to resolve changes in reservoir conditions on a spatial scale of 50 m, say, then an effective continuum approximation should be applicable only when fracture spacing is less than 1 m. These numbers are meant to give an order-of-magnitude estimate for the fracture spacing required to justify application of the effective continuum approach.

Persistent nonequilibrium conditions between matrix and fractures, and the accompanying transient interporosity flow effects can be modeled with the method of "multiple interacting continua" (MINC; Pruess and Narasimhan, 1982, 1985). An extension of the well known double-porosity method (see Figure 1; Barenblatt et al., 1960; Warren and Root, 1963), the MINC method combines features of both the explicit fracture and effective continuum approaches. The fracture system is modeled as a continuum, which interacts with several matrix continua. The latter are defined based on the following consideration. Due to vastly different diffusivities, exploitation-induced perturbations in thermodynamic conditions in a fractured reservoir will propagate rapidly through the network of interconnected fractures, while invading the matrix blocks only slowly. Responding to the changing conditions in the fractures, the thermodynamic conditions in the matrix blocks will then change in a way that is primarily controlled by the distance to the nearest fracture. This concept leads to a discretization of matrix blocks into a series of nested volume elements, as schematically shown in Figure 2. Flow in this system can easily be modeled by means of the integral finite difference technique, which only requires specification of grid block volumes, interface areas, and nodal distances (Pruess, 1983a). The concept of discretizing matrix blocks according to distance from the nearest fracture can also be applied to irregular and stochastic fracture distributions (Pruess and Karasaki, 1982). If only two continua (one for the fractures, one for the matrix) are specified, the MINC method reduces to the double-porosity approach.

The accuracy of the MINC method has been demonstrated by comparison with analytical solutions (Lai et al., 1986), with explicit fracture calculations (Wu and Pruess, 1988), and with laboratory experiments (Lam et al., 1988). We have recently developed a simplification of the MINC method that is applicable to the problem of heat exchange with impermeable matrix blocks (Pruess and Wu, 1988). The simplification obviates the need for subgridding of matrix blocks; instead, temperature in the blocks is represented by means of a simple trial function, as follows (Vinsome and Westerveld, 1980):

$$T(x,t) - T_i = (T_f - T_i + px + qx^2)\exp(-x/d) \qquad (1)$$

Here x is the distance from the block surface, T_i is initial block temperature, T_f is the time-varying temperature in the fractures (at the block surface), p and q are time-varying fit parameters, and d is the penetration depth for heat conduction, given by $d = \sqrt{(Dt)}/2$, where D is the thermal diffusivity of the blocks. The parameters p and q are calculated at each time step of a simulation run from requirements of energy conservation in the blocks, and continuity of heat flux at the block surface. This semi-analytical approach to interporosity flow can give accurate results with no noticeable increase in computational effort compared to simple porous medium models. A completely analogous approach can be used to calculate fluid exchange with permeable blocks in single-phase liquid reservoirs.

APPLICATIONS

Geothermal reservoir simulators have been used to model laboratory experiments, to study fundamental aspects of geothermal

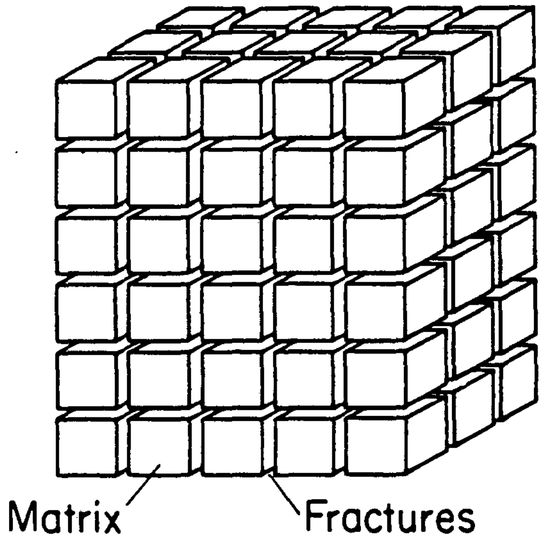

Figure 1. Idealized double-porosity model of a fractured porous medium.

reservoir dynamics, and to perform simulation studies for specific geothermal fields. Although only few applications to laboratory experiments have been made, these are important for confirming the basic physics of fluid and heat flow incorporated into the simulators (Verma et al., 1985; Lam et al., 1988). The study of reservoir dynamics has been a fruitful application of numerical simulators (see Table 1), and has helped in developing a better understanding of fluid and heat flow mechanisms in geothermal reservoirs. Basic insights into the exploitation of different kinds of geothermal systems have been gained, and issues in well testing of nonisothermal multiphase systems have been clarified.

From a practical viewpoint the most interesting applications of reservoir simulators are for history matching and performance prediction of specific geothermal fields. A number of field case studies have been published (see the recent reviews by O'Sullivan, 1985, and Bodvarsson et al., 1986), and a considerably larger number remains unpublished because of proprietary restrictions on the data. We believe that the existing studies have shown that it is indeed possible to build sufficiently quantitative and reliable models of geothermal fields to reproduce observed field behavior (history matching), and to be able to obtain useful guidance for field development and management.

Table 1. Advances in Reservoir Dynamics from Numerical Simulations

- Pressure decline in the depletion of boiling reservoirs
- Evaluation of boiling and condensation zones
- Reservoir exploitation strategies
- Liquid-vapor counterflow systems (vapor-dominated and liquid-dominated heat pipes)
- Transition from liquid-dominated to vapor-dominated conditions
- Natural evolution of hydrothermal convection systems
- Fluid and heat transfer in fractured-porous media
- Non-isothermal and two-phase well testing
- Effects of reinjection and natural recharge
- Non-condensible gas effects

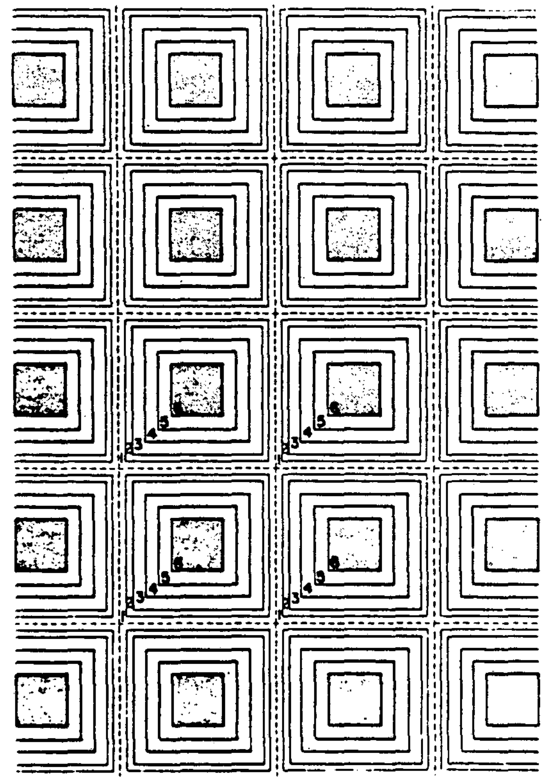

Figure 2. Basic space discretization in the method of "multiple interacting continua" (MINC; after Pruess and Narasimhan, 1982).

RESERVOIR DYNAMICS

The versatility of geothermal reservoir simulators has made possible applications to a wide range of fluid and heat flow problems. Table 1 lists the main areas in which numerical simulation studies have produced significant advances in our understanding of geothermal systems.

Applications of the MINC method have produced valuable insights into fluid and heat flow conditions in fractured boiling reservoirs. For example, a mechanism of conductive enhancement of flowing enthalpy was discovered which will cause superheated steam to be discharged from matrix blocks of low permeability, even if liquid saturation in the matrix blocks is large (Pruess and Narasimhan, 1982; Pruess, 1983b). Possible mechanisms for natural evolution of two-phase liquid and vapor dominated systems were demonstrated (Pruess, 1985; Pruess et al., 1987). The presence of non-condensible gases was shown to give rise to some unusual effects in fractured media (Pruess et al., 1985b; Bodvarsson and Gaulke, 1987).

Of particular interest in fractured geothermal reservoirs is their response to reinjection of heat-depleted waste waters. This could result in enhanced energy recovery, but it also raises the possibility of premature thermal breakthrough of reinjected waters along preferential pathways (major fractures or faults). Tracer tests can reveal such short-circuiting paths, but there is no general quantitatively useful relationship between breakthrough of tracer and thermal fronts. Simulation studies have suggested that thermal degradation at production wells should be largely reversible if the offending injector is shut in (Pruess and Bodvarsson, 1984). Injection studies in fractured two-phase and vapor zones have shown interesting fluid and heat flow phenomena (Pruess, 1983b; Pruess and Narasimhan, 1985; Bodvarsson et al., 1985; Calore et al., 1986). In a five-spot production-injection problem it was found that for 50 m fracture spacing a nearly complete heat sweep could be achieved, while for 250 m fracture spacing significant heat reserves were bypassed. This can be seen from Figure 3, which shows the simulated temperature profile in the fractures along a line connecting production and injection wells after 36.5 years of constant-rate production and 100 % reinjection (Pruess and Wu, 1988). The data for 50 m fracture spacing virtually coincide with a porous medium model, indicating excellent thermal sweep, while those for 250 m fracture spacing indicate substantial bypassing. Figure 3 also shows excellent agreement between results obtained from the semi-analytical method for interporosity flow and the MINC method.

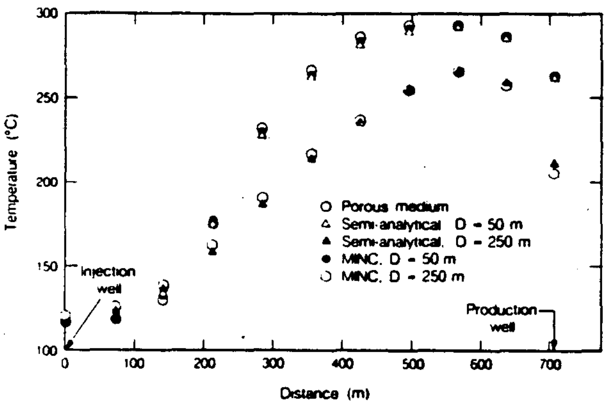

Figure 3. Simulated temperature profiles in five-spot production-injection system for different fracture spacings after 36.5 years (after Pruess and Wu, 1988).

WELL TESTING

Another practically important area in which much progress has been made through applications of numerical simulators is in the design and analysis of well tests in nonisothermal and two-phase systems. Interpretation of such tests is made difficult by highly variable fluid properties and nonlinear flow effects. Numerical simulation has provided a convenient and flexible tool for generating test cases that could then be used to evaluate the applicability of analysis techniques borrowed from isothermal single-phase flow. Grant (1978), Garg (1980), Grant and Sorey (1979), and Sorey et al. (1980) showed that under certain conditions pressure transients resulting from constant-rate production from two-phase zones can be approximately described with a linear diffusion equation. O'Sullivan and Pruess (1980), Schroeder et al. (1982), Benson and Bodvarsson (1982), and Bodvarsson et al. (1984) examined nonisothermal injection tests and found that semi-log analysis based on the line source solution was applicable to porous medium systems. Garg and Pritchett (1988) used numerical simulation to examine pressure interference tests in single-phase reservoirs that evolve a two-phase zone in response to fluid production. Simulation of nonisothermal well tests in fractured single- and two-phase reservoirs have shown very complex behavior that appears to defy simple analysis methods (see O'Sullivan, 1987, and references therein). Figure 4 shows simulated pressure buildups in response to constant-rate injection of water with an enthalpy of 500 kJ/kg (corresponding to approximately 120 °C) into a fractured reservoir with single-phase liquid at an initial temperature of 240 °C. Matrix blocks are assumed to be cubes of 10 m side length. The buildup for permeable blocks displays varying curvature with no straight-line segments. Agreement between results obtained from a semi-analytical representation of interporosity flow and the MINC method is excellent. Additional complications arise in fractured media from the common presence of several well feeds at different temperatures. This can give rise to large and persistent internal wellbore flows with strong pressure effects which, if not recognized as such, would lead one to draw erroneous conclusions on formation properties (Grant et al., 1982; Ripperda and Bodvarsson, 1988). Large pressure effects can also occur from vertical upflow of steam in response to saturation changes near producing wells (Bodvarsson et al., 1987).

It appears that much work remains to be done in the interpretation and analysis of nonisothermal and two-phase well tests, and that numerical simulation will continue to serve as the premier investigative tool in these studies.

FIELD STUDIES

A number of simulation studies for specific geothermal fields have appeared in the open literature (see the reviews by O'Sullivan, 1985; Bodvarsson et al., 1986). A considerably larger number of studies remains proprietary in the files of engineering consulting firms and geothermal operators. In the present paper we will not attempt to review specific case studies; rather we wish to discuss some general issues that arise in the application of numerical reservoir simulators to geothermal fields.

Simulators are constructed on the basis of sound physical laws of fluid and heat flow, and employ sophisticated mathematical and numerical techniques to quantify these phenomena. The process of numerical reservoir simulation, however, is a much more subjective and uncertain endeavour. The starting point is a conceptual model of the field, which is arrived at in a highly intuitive manner by integrating the ideas of the diverse specialists that participate in field exploration and development. Depending upon the most significant field development issues at hand, simulation models of different degree of detail and comprehensiveness can then be constructed. In order to be able to make credible predictions of reservoir response to exploitation it is important that proper initial conditions be used. The issue of initial conditions is especially important in two-phase reservoirs, where large pressure and enthalpy effects can result from the initial distribution of liquid and vapor phases which usually is highly uncertain. Consistent initial conditions can be obtained from careful modeling of the natural state, including upflow and discharge zones, surface manifestations, and trends in chemical composition of the geofluids. Natural state modeling entails a very considerable effort, which in practice is often shortcut under pressure from more immediate problems arising in field development.

Typical questions which numerical simulation may be called upon to answer relate to (i) the generating capacity of a field, (ii) future rates, enthalpies, and chemical composition of well discharges, (iii) identification of drilling targets, (iv) optimal well spacings and completions, and (v) design and impact of reinjection of heat-depleted fluids. Most reservoir engineers would agree with the proposition that a reliable prediction of reservoir performance could be achieved if only sufficiently detailed and reliable data on the thermodynamic and hydrologic structure of a

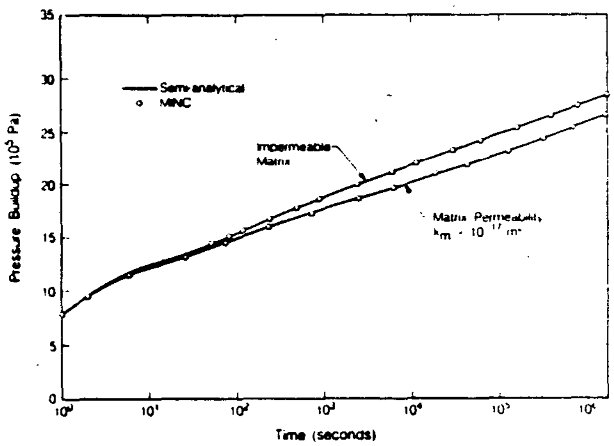

Figure 4. Simulated pressure buildups for non-isothermal injection into a fractured reservoir.

geothermal field were available. However, in practice field data have been a notorious bottleneck that limits the reliability of simulation predictions. The reservoir engineer invariably must work with incomplete data of usually uncertain accuracy. Numerical simulation then becomes an often tedious trial-and-error process, in which rough estimates or guesses must be substituted where sufficiently detailed data are unavailable; these guesses must be refined until an acceptable agreement is found between simulated and observed reservoir behavior. Numerical fluid and heat flow models usually are not unique, and must be further constrained from geochemical, geologic, and geophysical data.

Applications of numerical simulators to specific fields can vary greatly in scope. At its simplest, simulation studies would be undertaken to address very specific issues, such as optimal well spacing, or the adequacy of a proposed reservoir mechanism to explain certain observed features. This sort of study can be done with schematic idealized models that only need to capture those reservoir features that are pertinent to the specific problem at hand. At its most ambitious, simulation models would attempt to be "all-encompassing," including a detailed three-dimensional representation of all significant hydrogeological features, and attempting to predict future deliverabilities of all wells individually in quantitative detail. The main value of the latter kind of modeling approach may perhaps not be found in the detailed predictive ability, which is questionable given the various uncertainties on different space and time scales, but in the push towards integrating the views of the different disciplines (geology, geophysics, geochemistry, reservoir engineering) into a single coherent model of the field. This integration of expertise may just lead to a better understanding of the field, and to better engineering decisions. It may also enhance the confidence of investors in the feasibility of a proposed geothermal project.

DISCUSSION AND CONCLUSIONS

A pervasive feature of geothermal reservoir evaluation is uncertainty. Our ability to characterize geothermal reservoirs, or any subsurface flow system, is and always will be limited. Predictions based on incomplete data of unknown accuracy cannot be more reliable than the data themselves. Numerical simulation can not provide any magic to fundamentally change these facts, but it can provide a tool to augment and supplement other approaches. For example, effects of uncertain reservoir conditions and parameters can be quickly and easily examined by means of sensitivity studies. Likewise, the pros and cons of alternative field development plans can be explored.

We believe that numerical reservoir simulation studies have made tangible impacts on geothermal energy development. Such studies have improved our understanding of fluid and heat flow dynamics in different types of geothermal systems. Important insights were gained into the design and analysis of well tests under nonisothermal and two-phase conditions. Simulation studies of production-reinjection systems with premature thermal breakthrough along major faults or fractures have dispelled some fears regarding reinjection. They indicated that, while such breakthroughs may not be entirely avoidable based on tracer data, they would be limited and largely reversible if the offending injector is shut in.

As far as the development of specific geothermal fields is concerned, an example of tangible impacts is provided by the studies undertaken for the Olkaria geothermal field, Kenya. An early study (Bodvarsson et al., 1982) indicated the desirability of completing wells in the deep liquid-dominated zone rather than in the shallow steam zone, because the former would permit a more uniform depletion of mass and heat reserves. More recently, Bodvarsson et al. (1987) demonstrated that an efficient long-term depletion of Olkaria could be accomplished with significantly lower well density than had previously been used in the development of the field. There are undoubtedly many more examples of tangible impacts on geothermal field development among the many simulation studies that have not been released to the public.

With geothermal reservoir simulation software and services in routine commercial use, it is of interest to speculate on future trends and possibilities in this field. Where is a need and a potential for major improvements in our simulation tools and their use? What are the possibilities and benefits for realizing improvements near-term as well as long-term?

Generally speaking, it would be desirable for simulators to become more realistic and comprehensive in their representation of physical and chemical processes in geothermal reservoirs. At the same time execution speed and ease of use should be improved.

Table 2 lists a number of specific items that should be considered for mapping out future research directions. Some fundamental reservoir processes require better definition. An example is multiphase flow in fractures, which is the dominant production mechanism in most high-temperature geothermal fields. Yet next to nothing is known about two-phase flow in "real" rough-walled fractures; an effort to develop laboratory experiments in this area has been initiated at LBL to supply some of the basic information needed. The coupling of chemical and mechanical processes to hydrology is not usually included in geothermal reservoir simulators, and geochemical and geophysical data are not usually input into or predicted from fluid and heat flow simulations (second point in Table 2). A broadened scope, possibly also including flow in wellbores and surface lines, could lead to more comprehensive and realistic reservoir models. Another area of possible improvement is in the mathematical and numerical techniques. Most of the numerical work in reservoir simulation is expended in the solution of large systems of linear equations. Efficiency gains in this area could make it possible to improve the geometric definition and realism of simulations, especially for three-dimensional problems. Furthermore, more chemical species could be included in flow models. Improved capabilities for tracking sharp phase or composition fronts are also desirable.

Table 2. Possible future improvements in geothermal reservoir simulation technology

(1)	Better definition and more complete description of reservoir processes
(2)	Broadened scope (geochemistry, geophysics)
(3)	Improved mathematical and numerical techniques
(4)	Better user interface/data handling
(5)	Application of expert system concepts (artificial intelligence)
(6)	More complete and reliable field data
(7)	Better application methodology through broader track record

A reservoir simulation effort involves working with large amounts of data which is a tedious and time consuming process. One could expect that substantial gains in efficiency may be possible from appropriate interactive and graphic techniques. The fifth point in Table 2, expert systems, relates to both broadened scope and better user interface. In the development of a simulation model of a geothermal field the reservoir engineer attempts to integrate and synthesize large amounts of information from different scientific and engineering disciplines. Help and advice from geologists, geochemists, and geophysicists is needed in this task. Expert systems could offer a way to make such multidisciplinary advice available at a desktop terminal in a convenient and efficient way.

The critical importance of field data (point 6) has already been pointed out. The final point in Table 2 suggests to continue building a track record of publicly available simulation studies, to improve our understanding of how to best use reservoir simulators and the results from them.

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