LBNL-48124

GEOTHERMAL RESERVOIR SIMULATION TO ENHANCE CONFIDENCE IN PREDICTIONS FOR NUCLEAR WASTE DISPOSAL

Timothy J. Kneafsey[1], Karsten Pruess[1], Michael J. O'Sullivan[2], and Gudmundur S. Bodvarsson[1]

[1] Earth Sciences Division
Lawrence Berkeley National Laboratory
University of California
Berkeley, California, 94720

[2] Department of Engineering Science
University of Auckland
Auckland, New Zealand

Abstract

Numerical simulation of geothermal reservoirs is useful and necessary in understanding and evaluating reservoir structure and behavior, designing field development, and predicting performance. Models vary in complexity depending on processes considered, heterogeneity, data availability, and study objectives. They are evaluated using computer codes written and tested to study single and multiphase flow and transport under nonisothermal conditions. Many flow and heat transfer processes modeled in geothermal reservoirs are expected to occur in anthropogenic thermal (AT) systems created by geologic disposal of heat-generating nuclear waste. We examine and compare geothermal systems and the AT system expected at Yucca Mountain, Nevada, and their modeling. Time frames and spatial scales are similar in both systems, but increased precision is necessary for modeling the AT system, because flow through specific repository locations will affect long-term ability radionuclide retention. Geothermal modeling experience has generated a methodology, used in the AT modeling for Yucca Mountain, yielding good predictive results if sufficient reliable data are available and an experienced modeler is involved. Codes used in geothermal and AT modeling have been tested extensively and successfully on a variety of analytical and laboratory problems.

Key Words

Nuclear waste disposal, simulation, geothermal, Yucca Mountain, post-audit

1.0 Introduction

Subsurface disposal of heat–generating, high–level nuclear waste, such as at the potential repository at Yucca Mountain, Nevada will induce changes in the thermal, hydrologic, and chemical processes that will occur for some distance from the waste for many thousands of years. These changes include water boiling within the rock, flow of the water vapor, condensation of the water vapor, flow of the condensate, mineral dissolution in the condensate, mineral precipitation upon boiling, and hydrothermal flows in the saturated zone. Understanding flow through the mountain in its natural state, during the heating phase, and as the mountain cools is necessary to adequately assess the protection provided by the repository, and to predict the behavior of the repository for a time scale of 10,000 years or more. To this end, investigators have constructed numerical models to study present moisture flow, analyze thermal test data, evaluate the impact of the imposed heat source on the local environment, and assess how both natural and anthropogenic thermal (AT) systems may affect the potential repository (Birkholzer et al., 1999; Buscheck, 1998; Buscheck and Nitao, 1993; Buscheck and Nitao, 1994; Haukwa et al., 1999; Nitao, 1988; Nitao et al., 1992; Pruess and Tsang, 1994; Pruess et al., 1984b; Pruess et al., 1990a; Pruess et al., 1990b; Tsang and Birkholzer, 1999; Tsang and Pruess, 1987; Tsang and Pruess, 1989; Tsang and Pruess, 1990; Wu et al., 1999).

In this paper, we critically examine fluid– and heat–flow modeling in geothermal systems and the potential nuclear waste disposal in the unsaturated tuffs at Yucca Mountain. In both of these areas, the same basic processes and phenomena have been shown to be important including multiphase heat and mass transfer, capillary effects, vapor pressure lowering, dispersion, solute and colloid transport, and mineral dissolution and precipitation. We review the modeling process used in the geothermal industry, methods for determining the parameters used in these models, and discuss comparisons between predicted and observed reservoir behavior. We also discuss verification tests applied to show that codes and modeling techniques function properly for the processes considered.

The potential repository at Yucca Mountain would be constructed in a thick (600–700 m) unsaturated zone (UZ) comprised of layers of rhyolitic tuffs with varying degrees of welding and alteration. The welded units tend to have low matrix permeability (microdarcies) but significant porosity (~10%), and are fractured with high fracture permeability (darcies). The nonwelded units are less fractured, but have higher permeability (hundreds of millidarcies) and porosity (~30%) (Bodvarsson et al., 1999). Alteration products resulting from natural and anthropogenic processes affect the transport of radionuclides, with clays and zeolites providing sites for ion exchange. In the repository, waste in corrosion–resistant canisters would be emplaced in drifts (typically 5 meter diameter tunnels) in a specified manner about 300 m below the ground surface and about 300 m above the water table. Continued radioactive decay of the waste would heat the local rock for hundreds of years (Pruess and Tsang, 1994).

Many of the processes expected to occur in the potential AT system at Yucca Mountain are commonly encountered in natural geothermal systems at similar size scales (Figure 1). Numerical modeling of natural geothermal systems has been performed since the 1970s, both to gain an understanding of their character and structure, and for exploitation of these resources for electricity generation and thermal energy extraction. The years of collective experience simulating geothermal reservoirs and their production has led to a modeling process capable of yielding reasonably accurate predictive results. These results are generally dependent on the field information and numerical simulation codes available and the abilities of the modelers.

Geothermal modeling efforts are often performed on a number of scales, including the laboratory, well, and field scale. At Yucca Mountain, modeling is performed (moving from the smaller to larger scale) on the laboratory scale, field experiment scales (several cubic meters such as in modeling the Large Block Test), drift scale (which is similar to the well scale in geothermal modeling), and the field scale. Suites of models have been generated to simulate these scales (Buscheck, 1998). Examples of geothermal field–scale models are discussed in Section 2, and the site–scale UZ model (Wu et al., 1999) provides an example of field–scale modeling at Yucca Mountain. Examples of modeling studies of laboratory–scale and field–scale experiments are presented in Section 3.

Various regions within the AT system would correspond to different types of geothermal and hydrothermal systems. After a period of time following waste emplacement, water would be boiled out of the rock matrix nearest to the heated drifts causing a dryout zone. Beyond this region, where water still is present in the rock matrix, the formation would heat up by thermal conduction and possible steam–water counterflow (heat pipes) in the fractures. Liquid flow in heat pipes above the potential repository will be primarily gravity–driven, while those below the potential repository will be capillary–driven and of smaller extent. This heat–pipe region is analogous to a vapor–dominated geothermal system. Beyond the heat–pipe region, heat transfer will occur primarily by conduction outward, with the temperature decreasing with distance from the repository. In this region, where temperature gradients are small, two–phase (air and water) flow would occur. Some thermal influences are also expected in the saturated zone at Yucca Mountain, resulting in a weak hydrothermal circulation (Buscheck and Nitao, 1993). High temperatures and pressures, which are routinely observed in geothermal systems and commonly handled by geothermal codes, are generally not expected in the AT system at Yucca Mountain.

Some differences in spatial and temporal scales in AT and geothermal systems should be noted. Typical geothermal systems are large in volume (cubic kilometers), and large quantities of water and steam are extracted from wells at specific locations within the system. The placement of these wells affects their performance, but because of the spatial extent of geothermal systems, some latitude exists in well placement. At Yucca Mountain, small quantities of liquid water at specific locations (where it may contact waste packages) are of concern. Because of this, water flow on the drift– and subdrift–scale at Yucca Mountain is also important. Flow diverted around drifts will not be available to promote waste package corrosion and radionuclide transport, but if flow intercepted by the drifts drips onto waste packages, it may enhance waste package corrosion and possibly radionuclide transport. Small–scale processes and heterogeneity influence flow processes and dripping in drifts; thus, the small scale (tens of centimeters) is important in evaluating the AT system at Yucca Mountain. In geothermal systems, spatial resolution of this level is neither feasible nor desirable. The size, location, and nature of the heat source are generally not well known in geothermal systems. In the potential AT system, however, high–level nuclear waste packages than provide a heat source with well–known magnitude and duration will be emplaced gradually in a specified manner over a spatially limited and well–defined region. The local placement and distribution of the heat–generating waste packages may affect hydrological and chemical processes, whereas in geothermal systems, heat input generally occurs over a much larger area.

Geothermal systems are generally modeled for time scales different than those for the AT system. While natural–state modeling (generally performed by applying a heat source to a system under a natural thermal gradient at some time in the past and predicting the system that currently exists) may be performed for time scales of tens of thousands to millions of years, prediction of commercial energy extraction from geothermal reservoirs is generally considered over time frames of 20–50 years. The predictive time frame of interest of the AT system is on the order of tens of thousands of years or more, whereas the duration of field tests is only up to several years. In terms of time frame and methodology, the predictive requirements of the AT system are similar to the natural–state modeling of geothermal reservoirs.

From the experience gained in setting up, calibrating, and using many site–specific reservoir models, a basic approach to building and calibrating numerical models has evolved. This process is discussed in Section 2 (see also O'Sullivan 1985, and Bodvarsson et al. 1986). The performance of site–specific models of geothermal reservoir is discussed in Section 3. With site–specific models, there are a few cases in which the elapsed time since models were first established is sufficiently long to allow comparison of model predictions against actual field performance. In Section 3, we also discuss (semi–)analytical, laboratory, and field data used to confirm the performance of simulators.

Several phenomena that occur in geothermal systems and are expected in the AT system at Yucca Mountain will not be addressed here. These include the effects on flow resulting from the dissolution and precipitation of minerals, colloid generation and transport, mineral alteration, ion exchange, retrograde mineral reactions, and rock deformation. Although some of these processes have been modeled previously (Lai et al., 1985; Malate and O'Sullivan, 1992; Mangold and Tsang, 1983), consideration and modeling of many of these processes is in early stages (White, 1995; White, 1997; White and Mroczek, 1998; Xu et al., 1998). For many of these processes, field and laboratory verification is yet to be accomplished.

2. Modeling Geothermal and AT Systems

2.1 Introduction

Although modeling of geothermal and hydrothermal systems has been performed for three decades, the effective starting point was the Code Comparison Study in 1980 (Stanford Geothermal Program, 1980), which compared several geothermal simulators on a suite of six test problems. In this effort, satisfactory agreement between the simulation programs on solving these fluid and heat flow problems was demonstrated. Since that time, the experience of developing site–specific models as well as generic reservoir modeling studies have led to a steady improvement in the capabilities of geothermal reservoir simulation codes (see Pruess et al., 1998). A major thrust of modeling research has been in fundamental studies of physical and chemical processes that control the behavior of hydrothermal systems (Pruess, 1990; Pruess et al., 1998).

In recent years, modeling of the extensive UZ of the potential high–level waste repository at Yucca Mountain, both in its natural state and possible future state (under conditions of thermal perturbation), has been a major application for codes originally developed for geothermal/hydrothermal modeling (Wu et al., 1999). The emplacement of spent nuclear fuel in the unsaturated tuffs at Yucca Mountain will provide a heat source that will endure several hundred years. Although this heat source may be somewhat short–lived in comparison to many geothermal systems, it is still expected to create an AT system having similar characteristics to some geothermal systems.

Both lumped and distributed parameter models have been used in geothermal reservoir simulation, with the simplest models of geothermal fields being lumped parameter models (Bodvarsson et al., 1986; Bodvarsson et al., 1984c). These consist of one or two blocks representing the entire system and can only model very large–scale average behavior. Few natural systems can be represented satisfactorily without including spatial variation; consequently, distributed parameter models (having multiple gridblocks with parameters that vary with location) have been extensively developed and will be considered further here.

2.2 Modeling Method

The geothermal reservoir modeling process can be described by a series of steps (O'Sullivan et al., 2001):

1 Data collection
2 Conceptual model development
3 Computer model design
4 Natural state modeling
5 History matching
6 Prediction of future behavior

These steps are often followed sequentially, but some iteration is usually required. For example, the natural–state modeling and history–matching steps will often lead to a review of the conceptual model and some redesign of the computer model. The collection of additional data, may affect all subsequent steps.

To construct a conceptual and numerical model, any and all interpretable data are considered. These data can be obtained from topographic maps, physical expressions of subsurface processes (such as hot springs and fumaroles), core and fluid samples, well logs (including temperature, lithology, electrical resistivity), well flowtests, fluid chemistry, self–potential surveys, precision gravity surveys, and other techniques. The geologic structure will provide the strongest overall influence on the behavior of mass and heat transfer in a reservoir; thus the lithology, locations of more and less permeable zones, and amount of fracturing are extremely important. Hot springs and fumaroles vent heat and mass from the geothermal system, providing information about the system. Testing of core samples provides an initial estimate of the rock matrix properties such as permeability, porosity, and thermal conductivity. Properties measured from core samples are valid on the scale measured. Thus, when considering much larger scales, such as gridblocks on the order of hundreds to thousands of cubic meters, these values require appropriate scaling and interpretation to account for fracture permeability and porosity as well as heterogeneity. Geophysical techniques such as electrical resistivity and acoustic methods can provide information over a scale of several meters. Well flow testing and subsequent modeling provide information about permeability and porosity in the region of the flowing zones of the well (Antunez et al., 1990; Bodvarsson et al., 1984a; Bodvarsson et al., 1990b; Bodvarsson et al., 1987a; Bodvarsson et al., 1987b; Doughty and Pruess, 1992; Menzies et al., 1991; Menzies et al., 1996; O'Sullivan, 1981; Pruess, 1990; Pruess et al., 1984a). Self–potential surveys can provide information on the size and location of flowing hydrothermal systems (Nishi et al., 1998), and microgravity data and their spatial and temporal variations can aid in the location of vapor–dominated regions and indicate changes in their size (Atkinson and Pedersen, 1988; Hunt et al., 1990). Seismic methods can aid in evaluating saturation changes in boiling reservoirs and can provide information on the migration of injected fluid.

At Yucca Mountain, an extensive effort has been applied towards collecting data. This includes geological mapping, installation and testing of boreholes, and core collection (as is often performed at geothermal reservoirs). Additionally, two multikilometer–long tunnels under the mountain have provided a myriad of samples and an underground laboratory for hydrologic and thermal tests (Birkholzer and Tsang, 1996; Birkholzer and Tsang, 1997; Fabryka-Martin et al., 1998; Lin et al., 1998; Sonnenthal et al., 1998; Tsang et al., 1999a; Tsang et al., 1999b; Tsang and Birkholzer, 1999; Yang et al., 1998). Results from the modeling studies accompanying these tests have provided not only parameter refinement, but also enhanced process understanding. However, despite the large amount of data collected, uncertainties persist, particularly in more sparsely sampled strata in the mountain.

Several tests have been performed in the Yucca Mountain tuffs in which heat has been applied and the system monitored. In the Large Block Test, a 3 x 3 x 4.5 m rock block was isolated from the welded tuff outcrop. Heaters were placed in five horizontal boreholes 2.75 m below the top, and the rock was heated to 140^{o}C. Temperature, relative humidity, electrical resistance, thermal conductivity, and pressure within the block were measured, as well as block deformation (Lin et al., 1998). In the Single Heater Test, a 4 kW heater was placed in a horizontal borehole in a subsurface test block flanked on three sides by 5 m long drifts (Tsang et al., 1999a). Moisture redistribution, formation permeability to air, temperature, and deformation were measured. The Drift Scale Test is the largest thermal test performed at Yucca Mountain. This test is located in a mined 47.5 m long drift and contains nine canister heaters, each with a maximum power of 7.5

kW. Twenty–five “wing heaters” for control of boundary conditions were placed in horizontal boreholes on each side of the drift with a maximum heat output of 143 kW (Hardin and Chestnut, 1997). Thermal, hydrologic, mechanical, and geochemical changes are monitored using more than 80 instrumented boreholes.

Once field and laboratory data have been collected, a conceptual model can be developed. A conceptual model is an abstraction of the physical system. This abstraction includes the physical and chemical processes considered important, system geology, geometry, hydrology, boundary conditions, and initial conditions. The conceptual model is usually formalized by constructing several diagrams representing plan views and vertical sections through the geothermal system. These diagrams show the main features and structure of the geothermal system such as the approximate permeability structure, the size and location of surface outflows, deep inflows, major faults, and resistivity boundaries, and depict how heat and mass are moving through it at a chosen scale. Construction of the conceptual model requires the synthesis of data from several disciplines, including geology, geophysics, geochemistry, and reservoir engineering. Some of the data may not be consistent, and the data sets are always incomplete. Because of this, judgment and experience as well as a good understanding of subsurface heat– and mass–transfer processes are required for conceptual model building.

At the next stage in the design of the computer model, decisions must be made about the following matters:

1 The size and shape of the region to be modeled
2 Grid design (spatial resolution)
3 The boundary conditions to be imposed on the model
4 The fluids and chemistry to be used (pure water, gases, dissolved salts)
5 Model parameter values (permeabilities, porosities, relative permeabilities, fracture spacing, etc.)

The numerical model should be designed so that it can closely parallel the conceptual model. Site–specific models are usually large three–dimensional models with hundreds to thousands of gridblocks; however, smaller one– and two–dimensional models are also used. UZ models at

Yucca Mountain are three–dimensional, with as many as one million gridblocks (Zhang et al., 2001). One– and two–dimensional models are also used when reasonable for parameter calibration and thermohydrologic studies.

Once the model has been designed, the modeling of the natural (undisturbed) state and evolution of the geothermal system can be carried out. In natural–state modeling, a heat and fluid source is applied to the system previously existing under a natural thermal gradient at some time in the past and predicting the system that currently exists. Fluid sources (upflow and recharge) may also be specified. This provides a means to evaluate the conceptual model and allows the calibration of some model parameters, such as permeability, thermal conductivity, and heat and fluid source strength. Natural states are slowly varying (nearly steady) and therefore are insensitive to storage–type parameters such as porosity and heat capacity. The procedure listed below is followed:

1 Assign values for the permeability of each block.
2 Assign the location and magnitude of deep heat and mass inflows and discharges.
3 Run the model to simulate the geothermal system development over geologic time.
4 Compare the temperature, pressure, and permeability distributions in the model with measured data of the existing system.
5 Compare the surface heat and mass outflows with measured or estimated values.
6 Adjust parameters such as permeability and the location and magnitude of deep inflows of heat and mass.

Repeat steps (1) – (6) until a reasonable fit between model results and field data is obtained.

Step 6, the adjustment of model parameters, is the key to this procedure. It is often difficult to know which parameters should be changed, and by how much, to improve the fit between model results and field data. Frequently, this process must be repeated many times to generate a suitable numerical model (Bodvarsson et al., 1984c; Hanano, 1992; O'Sullivan et al., 1990; Pritchett, 1995; Pritchett et al., 1991). Recent advances in inverse modeling have enabled this process to be partly automated (Bullivant and O'Sullivan, 1998; Finsterle, 1999; White, 1997). Many properties (such as a refined permeability structure) and field features (such as faults, and locations and sizes of inflows into the system) are inferred in this calibration stage. Parameters generated in natural state modeling are generally non–unique: alternative property sets may provide similar results. The properties must be constrained by the modeler's judgment to those that are most appropriate for the system. In addition, these parameters are specific to the type of model and not generally translatable to different model types of the same system. For example, a property set calibrated using an effective continuum model would not be directly applicable to a dual–permeability formulation (Doughty, 1999). At Yucca Mountain, significant effort has been devoted to model parameter assignment, using results from core testing, permeability testing, geophysical techniques, geothermal temperature–gradient matching, trial and error techniques, and inverse modeling. These efforts have resulted in parameter sets for the many geologic layers at the site (Bandurraga and Bodvarsson, 1999; Wu et al., 1999).

The evolution over time of the natural system has been studied in a few hydrothermal reservoir–modeling studies (Hayba and Ingebritsen, 1997; Ingebritsen and Sorey, 1988). Comparison of these modeling results to geologic and geochemical data (such as geochronometers, mineralogic information, and properties of fluids in inclusions) provides an idea of how appropriate the calculations describing the modeled processes are. Work on fluid inclusions (Moore and Adams, 1988; Moore et al., 1989) provides geochemical evidence supporting modeling studies of the very long–term (geologic time) natural behavior of geothermal systems, constraining time frames for natural–state modeling.

If the geothermal system has been perturbed by exploitation, then history matching can be used to further calibrate the model, particularly to obtain storage–type parameters such as porosity. In this stage, permeabilities, porosities, and recharge coefficients are varied. History–matching simulations for a geothermal system use the results of the natural state simulation as initial conditions. The model results are matched to pressure histories, production flow rates and enthalpies, and sometimes production chemistry. When simulations do not fit measurements, revision of the conceptual model and reevaluation of the natural state model may be required.

Once the computer model has been calibrated by natural–state modeling and possibly history matching, it can be used to make predictions about the likely future behavior of the system. However, before the model is used to make predictions about a future scenario, some preliminary future–scenario simulations should be performed to ensure that the model includes a large enough total area and depth so that its behavior over the time scale of interest is not unduly influenced by potentially artificial boundary conditions.

3. Geothermal Reservoir Performance Simulations

An extensive recent review of site–specific modeling studies by O'Sullivan et al. (2001) summarizes geothermal modeling at nearly 100 geothermal fields. In addition, simulations of generic reservoir problems have been valuable in posing and answering "what–if" questions, in code development, and in understanding of physical processes. Our interest here is to examine simulations of geothermal fields, particularly those with similarities to the potential AT system at Yucca Mountain. O'Sullivan et al. (2001) note that several codes were commonly used in geothermal reservoir modeling (e.g. TOUGH2, TETRAD, GEOSIM, AQUA, SING, STAR). A large proportion of published studies used early or current versions of the TOUGH2 code (Pruess, 1991), and greater consideration is afforded to studies using this simulator in the following sections.

3.1 Summary of Modeling Studies

A number of geothermal field models of interest to Yucca Mountain are summarized in Table 1. These were selected because they are either vapor dominated or contain two–phase regions (both liquid water and water vapor). Vapor–dominated or two–phase reservoirs were emphasized because they feature the processes of most concern in the AT system at Yucca Mountain: boiling, condensation, mineral precipitation, mineral dissolution, heat pipes, unsaturated flow of liquid water, water vapor, and noncondensable gases. Although a weak hydrothermal system may develop in the saturated zone at Yucca Mountain, we focus here on processes in the UZ. To better understand the modeling performed on each of these reservoirs, we tabulated a number of attributes, including the computer codes used, the number of dimensions (1–3), size of the computational mesh (number of gridblocks), physical size modeled, calibration method and time frame (if reported), and prediction time frame. Some of the inferences from the calibration studies are also listed in Table 1.

From Table 1, we see that the modeling efforts for the AT and geothermal fields are primarily three dimensional, with some earlier models being two–dimensional. The physical size modeled at Yucca Mountain is smaller than some geothermal fields such as Amatitlan (Guatemala), The Geysers (U.S.), or the Monteverdi Zone of Larderello (Italy), yet substantially larger than other fields such as Cove Fort Sulphurdale (U.S.). At Yucca Mountain, the size of the physical system is well known, constrained by the ground surface, the water table, physical processes, and repository design. In contrast, the boundaries of geothermal systems are often poorly known. An example of this is The Geysers (U.S.) where drilling has not encountered the bottom of the reservoir. The site–scale model at Yucca Mountain is discretized into up to 1,000,000 gridblocks, far greater than used for geothermal models (which at most have several tens of thousands of gridblocks). This greater number of gridblocks is complemented by a large amount of physical data, collected from numerous boreholes, wells, and large–scale tunnels with internal boreholes as well as a myriad of sampling locations within the rock strata of interest. Although less data are generally collected at geothermal reservoirs, the data available are normally precisely those quantities that will be predicted by the model (flow rates, pressures, temperatures, enthalpies) and it is often gathered over the scale of interest (e.g., well test).

Natural–state modeling is performed in nearly all the studies presented, and history matching is performed in several. Long history–matching studies have been performed for The Geysers (with 30 years of production data), and Wairakei (New Zealand), which began production in 1953. Prediction time frames for geothermal fields are on the order of 10 to 50 years. A general rule of thumb accepted in the geothermal–modeling community is that predictions for a well–studied geothermal field are valid only for a time scale on the order of magnitude of the history–matching data (Bodvarsson et al., 1993). This stems from uncertainties in assigning parameters to the model resulting from conflicting data and the lack of access to the physical system. The duration for which confidence in predictions is high will be much higher for well–bounded systems having adequate, high–quality data. For the AT system at Yucca Mountain, the collection of history–matching data to provide for a 10,000–year period of model confidence is impossible. Tests applying thermal perturbations to Yucca Mountain are planned for as long as eight years. Because of this, the modeling efforts for the potential repository have investigated potential behavior for a large range of possible conditions, including higher and lower percolation fluxes resulting from climate changes, different heat loads, different waste package arrangements, and sensitivity analyses have been performed for a variety of parameters (Bandurraga and Bodvarsson, 1999). In geothermal or AT systems, models can at best only approximate system behavior. With geothermal systems, modeling success is dependent on continued incorporation of data and reevaluation of the model. For the AT system, the reliability of modeling will also be enhanced by continued data collection and incorporation.

3.2 Aims of Modeling Studies

Simulation of geothermal reservoirs is generally performed to help determine a strategy for reservoir exploitation. These simulations provide a guide for the rates of fluid extraction from these reservoirs and for locating new wells, with emphasis on the maximum economic benefit over the projected lifetime of the geothermal field. Inferences about the structure of the reservoir and how heat and mass are transferred through it are made in performing many of these studies, providing information useful for exploitation.

Simulation of the AT system at Yucca Mountain serves to assess the suitability of the site as a geologic repository for nuclear waste. The goals of the repository are very different from geothermal reservoir exploitation, and the simulations of the repository in both its natural and thermally perturbed state reflect these goals. The design objective of the repository is to retain disposed radionuclides within its boundaries for an extended time (on the order of 10,000 years or more). Repository performance depends on (1) the amount of water that may seep into waste–emplacement drifts and carry radionuclides away from the repository, (2) the temperature and humidity near the waste packages (affecting the corrosion of the packages), and (3) the ability of the natural system to sorb and retain radionuclides that might escape the containment in the repository (Bodvarsson et al., 1999). These goals have required significant modeling of smaller–scale processes (in addition to the larger–scale geothermal–type modeling) to examine flow and transport processes to the accessible environment.

3.3 How Reliable Are Numerical Models of Geothermal Reservoirs?

Some general considerations are helpful to gain a perspective on the possibilities and limitations of "validating" numerical reservoir models against actual observed field behavior. Numerical simulation of geothermal reservoirs has become standard engineering practice since the 1980s. More than 100 field simulation studies have been carried out since 1990 (O'Sullivan et al., 2001). With such a large base of experience, it would appear that evaluation of the reliability and accuracy of numerical field models should be easy, but in practice this raises some difficult issues. The purpose of most reservoir simulation studies is to calibrate (history match) a field model against monitoring and production data, often also including natural–state data, and then use the calibrated model for evaluating alternative field development scenarios. Important issues include the generating capacity of a field, and the siting and operation of production and injection wells. Reservoir modeling is often done early in the development of a field, with rather limited data. Calibration of a numerical model can be a challenging task, because field behavior may be affected in complex ways by unknown or uncertain reservoir conditions and parameters that are being adjusted during the calibration process.

Successful model calibration is generally taken as an indication that some degree of "realism" or "accuracy" has been achieved in conceptual–model and parameter choices. However, models are generally non–unique and invariably entail uncertainties. The reliability of reservoir models improves, and history matching becomes more difficult to achieve, when field data are available for a longer time period, and when additional constraints from natural state modeling and from direct measurements of reservoir parameters are taken into consideration. Successful model calibration indeed suggests that some degree of realism in conceptual model and reservoir parameters has been attained, but it provides little in the way of specific and quantitative information on the reliability of a numerical model. A more severe test of model accuracy and realism can be made by comparing predictions of future field behavior with observations.

The number of studies that have attempted to compare observed field performance against the predictions of a previously developed numerical model is rather limited, and only a few of them have been published. An additional difficulty in evaluating the predictive accuracy and power of numerical reservoir models arises from the fact that geothermal field development and operation tends to be an ongoing, dynamic process that often may be quite different from the future scenarios envisioned by the numerical models. Field validation of models is also limited by the nature, coverage, and resolution of data. The types of data that may be available to calibrate and test a numerical model include the following.

- Hydrogeologic and thermal parameters, such as permeability, porosity, compressibility, relative permeability relationships, fracture spacings and orientations, thermal conductivity, specific heat
- Contour maps of reservoir temperatures, pressures, and chemical concentrations
- Well data versus time, including pressure, temperature, flow rate, flowing enthalpy, and chemical concentrations
- Geophysical surveys, such as resistivity, seismicity, gravity, self potential, tiltmeters, to delineate reservoir conditions and changes.

Many different kinds of data, at different levels of spatial and temporal resolution, have been used in geothermal reservoir modeling, but the data available at any particular geothermal field are usually quite limited. Hydrogeologic parameters may be obtained by well logging and testing, occasionally augmented by laboratory measurements. These parameters are generally incompletely known and may involve significant scale effects, such as *in situ* permeabilities that are considerably larger than permeabilities measured on laboratory specimen, especially in fractured reservoirs. Data from well tests and laboratory measurements can provide important initial guidance for modeling, but many reservoir parameters must be determined indirectly by calibrating model predictions to field observations. Observations through boreholes represent "point" measurements, with good spatial resolution but very limited coverage of the reservoir volume, while data from geophysical surveys tend to have the opposite characteristics, less spatial resolution but better volumetric coverage.

In spite of the limitations summarized above, a considerable track record, most of which remains unpublished, allows a critical evaluation of the extent to which numerical reservoir models can describe real systems, with observation periods of up to 30 years and on spatial scales of several kilometers. Below, we present and discuss evidence for the accuracy of numerical models of specific fields, using published information as well as informal communications from people active in the engineering consulting industry, and also drawing from our personal experience in geothermal simulation.

Many geothermal fields have been modeled for decades, using calibrated models to provide guidance for field exploitation. Since the early 1980s, UNOCAL maintained 3–D models of geothermal fields in the Philippines (including Tiwi, Bulalo, and Salak) and U.S. fields (including The Geysers, Salton Sea, and Heber) (K. Williamson, personal communication). Modeling of the Wairakei geothermal field (New Zealand) has been performed since the late 1960s, including many types of models and levels of complexity (O'Sullivan et al., 1998). The Kawerau Geothermal Field (New Zealand) has also been extensively modeled for more than a decade (White, 1997). In many of these cases, the models have been upgraded over time, as new information, codes, and techniques have become available. However, the summed longevity of the models at a particular field indicates a significant degree of confidence in geothermal reservoir modeling. As part of the continuing model development, model performance is assessed or audited. Most of these postaudits have not been published because of confidentiality requirements. Three examples from two geothermal fields (Olkaria East, Kenya and Nesjavellir, Iceland) identified in the literature are summarized below. Additionally, the forecasts from several unpublished simulations with seven or more years of history were compared to reservoir behavior. These are briefly reviewed below.

3.3.1 Published Postaudits

Olkaria East Geothermal Field, Kenya

The Olkaria East Field contains a vapor–dominated zone underlain by a liquid–dominated region. In the initial model (Bodvarsson et al., 1987a; Bodvarsson et al., 1987b), five scenarios involving well spacing, reinjection, and power generation were studied for field exploitation. The three–dimensional model was calibrated against flow rates and enthalpy histories of all wells, with reservoir porosities, permeabilities, and well productivity indices used as adjustable parameters. Thirty–year predictions of field production were made, although it was recognized that predictions were likely valid only as long as the 6.5 years of matched history. A well spacing of 11 wells per square kilometer was seen as optimum for the assumed recharge conditions.

The postaudit by Bodvarsson et al. (1990b) showed that the field–wide total decline in steam rate agreed very well with predictions. This decline is important in the prediction of the number of replacement wells required, impacting the economics of energy extraction. A well–by–well comparison was also performed. The earlier model adequately predicted steam rates and their decline for about 75% of the wells (e.g. Figure 2), with some wells showing unexpected behavior. Some of the wells were recently drilled at the time of the earlier model and had very limited production history on which to base the earlier calibration, resulting in differences between predictions and observations. The model also predicted the relative contribution of different well–feed zones to the total flow fairly accurately. Following the postaudit, the new data were used for further calibration of the model, resulting in the average porosity being increased so that the model (based on the porous–medium approximation) would better represent the actual properties of the fractured reservoir. It was also concluded that the earlier data set used for history matching was of too short duration to accurately estimate the recharge zone porosity. Using the newly recalibrated model, predictions of the required number of replacement wells were made for the next 30 years for the case of no reinjection. A slight decrease in number of replacement wells was predicted in the postaudit modeling. The authors felt confident that the model was useful as a reservoir–management tool.

Nesjavellir Geothermal Field, Iceland

The Nesjavellir Geothermal Field is a high–temperature liquid–dominated field with an inferred extensive vapor–dominated zone in the upflow region (Bodvarsson et al., 1990a; Bodvarsson et al., 1991). In the 1986 model, geologic data from 18 wells, extensive reservoir studies, and flow testing of well tests were used to construct a conceptual model and a three–dimensional numerical model of the system. Natural–state modeling and history–matching simulations were performed, inferring the permeability and porosity structure. MULKOM (an earlier version of the TOUGH2 code) was used to evaluate the 300 gridblock, 950–connection model that used porous medium assumptions. Several reservoir exploitation scenarios were evaluated (Bodvarsson et al., 1991).

Bodvarsson et al. (1993)evaluated the predictions made using the 1986 three–dimensional model for pressure decline and enthalpy changes. In the postaudit, measurements were compared to predicted flow rates and enthalpies for the six–year period from 1987 to 1992. The authors reported acceptable agreement between modeled and measured data, particularly considering that the prediction time was longer than the 1–3 year calibration period. Flowrate declines were overpredicted for many of the wells (e.g. Figure 3), and produced enthalpy was overestimated for some of them. Pressure declines at several wells were overpredicted, indicating that the permeabilities used in the 1986 model were too low. The new data were used to recalibrate the model resulting in increasing permeabilities, and new predictions were made.

The 1992 model was audited and recalibrated in 1998 (Steingrimsson et al., 2000) because the model underestimated enthalpy decline in some wells. Recalibration led to a change in the conceptual model. Changes were needed to obtain better matches in the northwest portion of the field in simulated enthalpy decline (wells 11 and 16), simulated pressure decline (well 18), and temperature decline of 15°C at 1000–1500 m depth (well 7). To do this, wells 7 and 11 were assumed to be in good hydrologic communication, and cooler waters were assumed to invade the field at depth in the northwest. These waters cause the observed cooling at well 7 and enthalpy decline at well 11. Relatively minor changes in permeability and porosity distribution were also made in the wellfield. The new model matched well data better, but the long–term reservoir predictions remained unchanged.

3.3.2 Other Performance Confirmations

The Geysers, California

The Geysers is of special interest in connection with a potential nuclear waste repository in the unsaturated zone at Yucca Mountain because of some fundamental similarities between these systems: both are two–phase water–gas systems in fractured rock, with similar hydrogeologic properties of rock matrix and fractures. The predominant reservoir rocks at The Geysers, graywackes and felsic intrusives, have a permeability on the order of microdarcies (Williamson, 1992), similar to the welded tuffs at Yucca Mountain. Permeabilities of the fracture network are also similar, of order 10^{-12} m^2 in both systems.

The Geysers is the largest known vapor–dominated geothermal field, having an installed generating capacity that peaked near 2,000 MW in the late 1980s. In 1992, a three–dimensional, dual porosity model of the field was developed by GeothermEx consisting of 2,880 matrix blocks and 2,880 fracture blocks. Calibration was performed against the 32–year production history of the field, including the pressure trends from observation wells and field–wide isobaric maps (Menzies and Pham, 1995; Pham and Menzies, 1993). For the first seven years following the prediction, the forecasts of well productivity and pressure decline proved accurate (S. Sanyal, personal communication). Following the seven–year period, the injection strategy at The Geysers was changed. A new 5,760–gridblock, dual–porosity model was developed and calibrated against the 39–year production history and using data from 642 wells (S. Sanyal, personal communication).

Cerro Prieto, Mexico

The Cerro Prieto Field had been in production for 17 years when modeled by Antunez et al. (1991). The field was initially liquid–dominated, but some dry steam was produced over time. A three–dimensional, 347 block, 135 km^2 x 4,500 m deep model was used to evaluate a proposed increase in production. Initial state and history matching were performed to calibrate the model. Two exploitation scenarios, no change or a production increase of 80 MW (to 700 MW) were evaluated for a 30–year time period, concluding that both options were feasible if deeper extraction can occur. The model does not fully account for inflow of cooler water.

Production history over a 10–year period indicated that the pressure and enthalpy forecasts from the model were reasonably accurate (S. Sanyal, personal communication). In 1999, a new three–dimensional model with 4,536 matrix and 4,536 fracture blocks was created and calibrated against the natural state, as well as 29 years of production and injection history from 242 wells. Three production scenarios were evaluated for a 30–year period (Butler et al., 2000).

Uenotai, Japan

The Uenotai Field is a liquid–dominated field with two–phase regions located in fractured rock. Conceptual and numerical models of this field were created following an extensive collection of data (Antunez et al., 1990; Robertson-Tait et al., 1990). A three–dimensional, two–phase model for the field was developed in 1989 with 358 blocks and a top layer with varying thickness (S. Sanyal, personal communication). Initial state and history matching were performed prior to predictions. The results of a 30–year prediction indicated a 30 MW development should be feasible. A slightly more detailed model, with 557 elements covering 40 km^2 x 2000 m depth in 4 layers was developed in 1993–94 (Pham et al., 1995). The predictions of well decline and number of make–up wells needed agreed well with actual field behavior. Enthalpy forecasts proved less accurate, which is attributed to the limited (1–2 years) history match period.

Mammoth, California

The Mammoth geothermal field is a single–phase, liquid–dominated field with a 40 MW power plant. In 1993, a 1,405–block three–dimensional model was developed and calibrated against the initial state and three years of production (pressure and temperature) history. The forecast of temperature decline proved remarkably accurate over the eight years following the prediction (S. Sanyal, personal communication). The modeling predictions at Mammoth were used to obtain a bank loan and to manage the field. If the field produced fluids below a set point temperature at any time during the 10–year bank loan duration, the loan could be recalled. The field reached the set point only after the pay back of the loan, as predicted (M. Pham, personal communication).

Heber, California

The Heber geothermal field is a single–phase, liquid–dominated field with an output of 86 MW. A 1,320–block, three–dimensional model was developed in 1992 and calibrated against the initial state and six years of history. At that time, two competing companies operated the two parts of the field. The model was used to evaluate fluid injection to maintain pressure on both sides of the field, resulting in injection along a line in the middle. This was placed in the steam delivery contract, and predictions matched the performance well. The predicted temperature decline matched observed temperature decline well for the 7–year prediction period. The model was updated, and predictions were made for the next 25 years (S. Butler, personal communication).

Geo East Mesa, California

Geo East Mesa is a portion of the larger East Mesa single–phase, liquid–dominated system, with an output of 40 MW. In 1993, a 6,700 block, three–dimensional model was developed and calibrated against the initial state as well as the pressure and temperature decline that occurred over the period from 1989 to 1992. The forecasts from the model proved accurate over the five years following the prediction, after which data were no longer available for comparison (S. Sanyal, personal communication).

Salton Sea, California

Commercial production of this high–temperature, hypersaline brine field began in 1982. A 297–block, three–dimensional model was developed in 1987 that included the salinity of the brine. The model was calibrated against the natural state (including the salinity distribution) and the pressure, enthalpy, and salinity from production up to that time. The predictions of pressure, enthalpy, and salinity proved reasonably accurate over the 14 years following the prediction. In 1995, another model was developed to forecast pressure, enthalpy, salinity, and zinc concentration for metal recovery. The 1995 model was calibrated against the initial state (pressure, enthalpy, salinity, and zinc concentration) and 13 years of production history from over 100 wells. The newer model has been further tuned as new data have become available, but verification will not be possible for several years until the salinity breakthrough occurs (S. Sanyal, personal communication).

Puna, Hawaii

The Puna geothermal field is a two–phase reservoir controlled by a single fissure and has produced 30 MW since 1993. Multiple modeling efforts have been performed (1993, 1994, 1996, and 1998) to better represent the system as data has become available. The forecasts of the 1994 model for steam and brine flow rates and wellhead pressure have proven accurate over the past 7 years (S. Sanyal, personal communication).

Steamboat Springs, Nevada

Commercial production of this single–phase, liquid–dominated system with 37 MW of power capacity began in 1986. In 1995, a 3,780–block three–dimensional model was developed and calibrated against the initial state and the pressure and temperature history over the 9–year production period. The forecast from this model has proved accurate over the past 7 years (S. Sanyal, personal communication).

3.4 Other Tests of Mathematical Models

Mathematical models of geothermal reservoir processes do not necessarily have to be formulated through space–and–time discretized numerical simulation approaches. For certain applications simpler analytically solvable models can be employed. Their success also adds confidence to our ability to model fluid and heat flow in geothermal systems. Examples include (semi–)analytical solutions employed in well testing that have been used in numerous applications to match observations and provide estimates of formation parameters (such as permeability–thickness, storativity, and fracture–matrix interaction parameters). Modeling of laboratory experiments has also significantly contributed to establishing the accuracy of numerical–simulation approaches. Below, we briefly describe several of the (semi–) analytical and experimental benchmarks that have been used in the confirmation of codes used in geothermal and AT modeling. We include single and two–phase isothermal and nonisothermal flow and transport.

We recognize that while codes are "verified" or "validated" by comparing model results to the (semi–)analytical or experimental results and therefore strictly confirmed for those cases only (Oreskes et al., 1994), the codes may be extended carefully from test problems to problems of larger significance. In doing so, we also recognize that real systems (including geothermal and AT systems) are open, and we have incomplete knowledge of the processes and structures affecting their performance. Because of this, interpretations of model results should reflect the extent of our understanding of the system and processes.

Single Phase Isothermal Flow and Transport

The Theis solution (one–dimensional radial flow to a well in an infinite, confined aquifer) is an important verification tool for isothermal single–phase incompressible flow (de Marsily, 1986). Analytic solutions of the advection–dispersion equation have been used for many simple reservoir configurations (Freeze and Cherry, 1979). In addition, the governing equation for flow is identical in form to the governing equation for conductive heat transfer, thus established and verified conductive heat transfer solutions (as from Carslaw and Jaeger [1986]) may be used to verify simulator results.

Verification of compressible single–phase gas flow has been performed by Pruess et al. (1996) using an analytical solution for one–dimensional radial flow in a well from an infinite reservoir (Kabir and Hasan, 1986). Excellent agreement between numerical results and the analytical solution was obtained (Figure 4). For radioactive decay, Oldenburg and Pruess (1995b) considered an analytical solution provided by Javandel et al. (1984) for the dispersive transport, sorption, and decay of radionuclides in saturated isothermal flow. Good agreement between analytical and numerical results was obtained. They also considered oxidation of ammonium to nitrite, using solutions provided by Cho (1971) and subsequently evaluated by van Genuchten (1985) and McNab and Narasimhan (1993). Coarse and fine spatial discretizations were used. Both provided good agreement with the analytical solution, but the fine discretization provided a better match (Figure 5). This study points out that in addition to the correct coding of the mathematical representations of the processes, the execution of the model must be appropriate to the spatial scales modeled.

For verifying dispersive transport, Oldenburg and Pruess (1993) used an analytical solution for saturated two–dimensional transport with dispersion presented by Javandel et al. (1984). Again, coarse and fine discretizations were used; with both providing good matches to the analytical solution (with the fine discretization more closely matching the analytical solution). Two single–phase isothermal problems have been used to evaluate flow affected by density differences. The Henry problem (Henry, 1964) considers salt water intrusion (flow of fresh water towards a more dense salt water). This problem has been modeled by several researchers, providing a high level of confidence in the results. Oldenburg and Pruess (1995a) obtained good agreement with simulation results of others for a comparable spatial discretization. The Elder problem (Elder, 1967) considers flow by either solutal– or thermally induced density differences. Again, this problem has been modeled by several researchers (Oldenburg and Pruess, 1995a); and Elder (1967) provided experimental data useful for validation. Oldenburg and Pruess (1995a) showed good agreement with simulation results of others, and with enhanced grid resolution, they were able to match experimental results better than previous researchers.

For transport through fractures, Wu and Pruess (2000) considered an analytical solution for tracer transport in parallel fractures (Sudicky and Frind, 1982). In the problem, a radionuclide is introduced into a fracture, transported by advection, hydrodynamic dispersion, and molecular diffusion. They obtained excellent agreement between the numerical and analytical solutions. In addition, Wu and Pruess (2000) considered a flow experiment (Sudicky et al., 1985) in which water with a nonreactive tracer followed by water without the tracer was introduced into a parallel layered silt/sand/silt lithology. This experiment was modeled as a fracture and matrix system, and the experimental data were used for model validation. With the parameters reported by Sudicky et al. (1985), Wu and Pruess (2000) obtained reasonable agreement between experimental and numerical results. However, better agreement was obtained when unmeasured parameters were adjusted within reasonable limits.

The extensive experience in well testing from both groundwater and oil reservoirs shows that the models fit field data very well. Many theoretical analytical techniques are available to gain significant information on the subsurface structure (de Marsily, 1986; Ehlig-Economides et al., 1994; Kuchuk, 1995; Shanyan and Wong, 1998; Thompson and Reynolds, 1997). Similarly, large–scale regional groundwater models have generally performed well (National Resource Council, 1990).

Several field–scale isothermal tracer experiments have been performed (Freyberg, 1986; LeBlanc et al., 1991; Mackay et al., 1986). In these field tests at the Borden, Canada, and Cape Cod, U.S., sites, a liquid slug containing conservative and nonconservative tracers was added at a location in the aquifer. In each case, an extensive array of multilevel samplers was used to collect data as the plumes moved. The data sets collected have been modeled in great detail, providing opportunities for exploring modeling methodologies and strategies for modeling chemical transport (Ezzedine and Rubin, 1997; Freyberg, 1986; Theirrin and Kitanidis, 1994).

Single Phase Nonisothermal Flow and Transport

A problem solved analytically by Avdonin (1964) considering cool water injected into a horizontal, semi–infinite, high–temperature aquifer at a specified mass flow rate, has been used for verification. The aquifer is confined on top and bottom by impermeable, adiabatic boundaries. Using midstream weighting, Moridis and Pruess (1992) obtained an excellent match to the analytical solution. Using the more robust upstream weighting, the match was not as good because of numerical dispersion. For validation, Moridis and Pruess (1992) used data from a laboratory convection cell experiment in a cylindrical porous medium heated from the inside and cooled on the outside (Reda, 1984). When channelized flow near the heater was considered (a fast flow pathway), the numerical results compared better with the experimental results. Cold water injection into one– and two–phase geothermal reservoirs, important for geothermal reinjection, has been studied analytically (Garg and Pritchett, 1990), yielding analytical solutions useful for code verification. The THOR code (Garg and Pritchett, 1990) was compared with the analytical solutions, achieving good agreement. Discrepancies were attributed partially to differences between the analytical and numerical solution in (1) global heat–conduction treatment, (2) well bore size, and (3) discretization.

The mathematical treatment of energy and mass accumulation are analogous. This allows for the use of thermal or chemical data to be used to verify/validate codes for chemical or thermal processes. Solutions for the Elder problem (Oldenburg and Pruess, 1995a), for example can be used for either solutal or thermal density difference induced flows.

Two–Phase Isothermal Flow and Transport

A one–dimensional infiltration problem consisting of horizontal infiltration of water into a semi–infinite homogeneous soil at an initial uniform saturation was first solved analytically by Philip (1955). Pruess et al. (1996) compared numerical solutions with the analytical solution for three interface weighting procedures. None of the numerical results differed from the analytical solution by more than 5%. Vauclin et al. (1979) performed an experiment useful for validation, consisting of infiltration into an unsaturated soil over a portion of the top boundary of a two–dimensional system. The unsaturated zone is underlain by a saturated zone, which is further underlain by a no–flow boundary. One of the vertical boundaries is a no–flow symmetry boundary, and the other vertical boundary allows for flow while maintaining the potentiometric surface at a constant level. Simulation results were generally within 90% of the experimental results, but information regarding heterogeneity in the experimental soil slab was not available or accounted for in the simulation, resulting in deviations (Moridis and Pruess, 1992). Two independent groups modeled these identical problems using the TOUGH2 code, with both groups achieving reasonable results on the 1–D infiltration problem, but only one group successfully modeling the 2–D infiltration problem (Moridis and Pruess, 1992). This indicates that the modeling approach is as important as the validity of the simulator. Oldenburg and Pruess (1995b) used an analytical solution by Shan and Stephens (1995) describing infiltrating water passing through a uniform vadose zone containing a region having a partially soluble, volatile chemical to verify a module (EOS7R) of the TOUGH2 code. Advection, diffusion, dissolution, volatilization, and sorption were considered. Agreement between the numerical simulation and the analytical solution was good (Figure 6).

Two–Phase Nonisothermal Flow and Transport

Doughty and Pruess (1992) extended an earlier similarity solution developed by O'Sullivan (1981) to semianalytically model heat and mass transfer in a homogeneous, isotropic porous medium in the region near an infinite linear heat source. This provided a problem useful for verification of two–phase nonisothermal flow. The solution considers air, water, and water vapor, but not gravity. Doughty and Pruess (1992) compare their modeling using the TOUGH2 code to the semianalytic solution examining the transient development of a heat pipe. A variety of cases were investigated with excellent agreement.

The effects of vapor pressure lowering may be verified by comparing model results with the Kelvin equation. Pruess et al. (1996) present a comparison of numerical and analytical results with less than 0.03% error. Pressure propagation in two–phase systems with phase change observed under carefully controlled laboratory conditions was observed and modeled by Herkelrath et al. (1983), showing that it is necessary to account for vapor pressure lowering effects.

For validation purposes, comparison of model results against experimental data is possible for a variety of conditions. In one case, temperature profile data are available for a vaporizing flow from a synthetic sandstone core (Kruger and Ramey, 1974). In the experiment, the 1–D saturated core was heated such that a linear temperature gradient formed. Then the core was placed in an oven at a uniform temperature, and one end was subjected to a time–dependent pressure. Temperature was measured over the length of the core. Two sets of numerical simulations–one including a representation of the oven, the other without the oven–bracketed experimental results, with a maximum error of about 5^{o}C (Figure 7). In another study, temperature data from an experiment in which liquid ether was introduced into the center of a superheated circular glass fracture analog were modeled (Fitzgerald et al., 1996). Temperatures were measured throughout the injection process and identified a nonisothermal liquid zone, a boiling zone, an isothermal vapor zone, and a nonisothermal vapor zone. The TOUGH2 code was used to model the experimental data, yielding good matches to the data across these zones.

Temperature data are also available from a laboratory–scale geothermal experiment that was performed in a large pressure vessel filled with granite blocks, heated, and then swept with cool water (Lam et al., 1988). These data were modeled using the MULKOM code, using Multiple Interacting Continua (MINC) (Pruess, 1991). When proper boundary conditions and thermophysical properties were used, a good match with experimental results was obtained.

3.5 Conclusions from Postaudit Studies

A large base of practical experience with geothermal reservoir simulation provides strong support for our ability to accurately model fluid–flow, heat–transfer, and mass–transport processes in geothermal systems. There are many examples of reservoir models that have successfully predicted temperatures, flow rates, pressures, and enthalpies at production wells over time periods of several years. The aggregated time periods of successful history matching and performance predictions of geothermal simulation models is estimated to be on the order of 1,000 years. The success of geothermal–reservoir studies suggests that the mathematical representation of the fluid flow and heat transfer processes incorporated in contemporary reservoir simulators are accurate. Practical limitations in building quantitatively accurate numerical models arise from uncertainties in boundary and initial conditions, reservoir parameters, and production and injection operations, not from limitations in the fundamental understanding and representation of physical and chemical processes.

The postaudit studies pointed out refinements necessary in the conceptual and numerical models of geothermal systems. Two major reasons have been identified for deviations between forecasted and field behavior: (1) the subsequent field operation was different from assumptions made in the model, and (2) the conceptual model did not accurately reflect the field. Additional difficulties in modeling geothermal reservoirs have been noted due to phase change, and to overconstraining the conceptual model by using core–scale parameters such as permeability to represent gridblocks without allowing for upscaling. Single–phase (either liquid or vapor) can be well represented by the models, but where phase change occurs, properly handling the relative permeabilities of the phases adds additional uncertainty. The postaudits provided an opportunity to fine–tune the conceptual model and make new predictions based on the refined models. As previously mentioned, the availability of any new significant data requires a re–evaluation and possible refinement of the conceptual and numerical models.

One conclusion from geothermal field studies is that each geothermal field has its own challenges for modeling and evaluations. Prior to the model construction and design, all relevant information from the field must be carefully evaluated. In general, there are different challenges in the modeling of single–phase and two–phase system. Single–phase liquid–dominated reservoirs have low overall system compressibilities, so that outer boundary conditions of the system become very important. Two–phase systems involve added complexities from heat–transfer effects on small spatial scales, as in near–wellbore boiling, and may be sensitive to relative permeabilities that are difficult to constrain on the reservoir scale.

4. Summary

Geothermal–reservoir modeling has been extensively and successfully used for decades in guiding reservoir exploitation strategies and gaining fundamental insights into the behavior of these systems. Over the past few decades, the quality of the computer codes, the capacity of the computers, and the ability of the modeling community has significantly increased, resulting in better models of geothermal systems. The modeling of an anthropogenic thermal system has been performed in parallel, with results used in possible design and management strategies of the potential repository. As with geothermal–system modeling, which is performed throughout the operating life of the project, the modeling of the AT system should continue into the operating life of the potential repository to allow for performance confirmation, upgrading of the model and repository design as needed, and improved predictions. Although some differences exist between geothermal and AT systems (and the associated modeling needs), strong similarities exist. These similarities relate to the physical processes, time scales, and physical size of the systems. Multiscale modeling is performed in both geothermal and AT systems to address processes that occur on smaller spatial scales, such as around wells in geothermal systems and near drifts in the AT system. Behavior on an even smaller scale is important for the AT system; thus, smaller–scale modeling is also being performed.

Although modeling of geothermal reservoirs has been largely successful, and evaluation and reevaluation of models, codes, and techniques have been extensively performed, little evidence is found in the literature in terms of published postaudits and lessons learned. These evaluations and sharing of lessons are extremely valuable for advancing the state of the art.

Acknowledgements

This work was supported by the Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, through Memorandum Purchase Order EA9013MC5X between Bechtel SAIC Company, LLC and the Ernest Orlando Lawrence Berkeley National Laboratory (Berkeley Lab). The support is provided to Berkeley Lab through the U.S. Department of Energy Contract No. DE–AC03–76SF00098. We thank Subir Sanyal, Steve Butler, and Minh Pham of GeothermEx, Inc., for generously sharing unpublished information from a large number of simulation studies with us. We also thank Stefan Finsterle and Marcelo Lippmann for their reviews of this manuscript and many helpful comments.

References

Antunez, E.U., Menzies, A.J. and Sanyal, S.K., 1991. Simulating a Challenging Water Dominated Geothermal System: the Cerro Prieto Field, Baja California, Mexico, Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 183-191.

Antunez, E.U., Sanyal, S.K., Menzies, A.J., Naka, T., Takeuchi, R., Iwata, S., Saeki, Y. and Inoue, T., 1990. Forecasting Well and Reservoir Behavior Using Numerical Simulation, Uenotai Geothermal Field, Akita Prefecture, Japan. Geothermal Resources Council Transactions, 14, PART II(August): 1255-1262.

Atkinson, P.G. and Pedersen, J.R., 1988. Using Precision Gravity Data in Geothermal Reservoir Engineering Modeling Studies, Thirteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 35-40.

Avdonin, N.A., 1964. Some formulas for calculating the temperature field of a stratum subject to thermal injection. Neft'i Gas, 3: 37-41.

Bandurraga, T.M. and Bodvarsson, G.S., 1999. Calibrating hydrogeologic parameters for the 3-D site-scale unsaturated zone model of Yucca Mountain, Nevada. Journal of Contaminant Hydrology, 38: 25-46.

Bertani, R. and Cappetti, G., 1995. Numerical Simulation of the Monteverdi Zone (Western Border of the Larderello Geothermal Field), World Geothermal Congress, 1995, Florence, Italy, pp. 1735-1740.

Birkholzer, J., Li, G., Tsang, C.-F. and Tsang, Y., 1999. Modeling studies and analysis of seepage into drifts at Yucca Mountain. Journal of Contaminant Hydrology, 38(Nos. 1-3): 349-384.

Birkholzer, J.T. and Tsang, Y.W., 1996. Forecast of Thermal-Hydrological Conditions and Air Injection Test Results of the Single Heater Test at Yucca Mountain. LBNL-39789, UC-814, Lawrence Berkeley National Laboratory, Berkeley, CA.

Birkholzer, J.T. and Tsang, Y.W., 1997. Pretest Analysis of the Thermal-Hydrological Conditions of the ESF Drift Scale Test. Level 4 Milestone SP9322M4, Lawrence Berkeley National Laboratory, Berkeley, California.

Bloomfield, K.K., Moore, J.N. and Sperry, T.L., 1998. Cove Fort-Sulphurdale Reservoir Numerical Simulation. Geothermal Resources Council Transactions, 22(September 20-23): 149-152.

Bodvarsson, G.S., Benson, S.M., Sigurdsson, O., Stefansson, V. and Eliasson, E.T., 1984a. The Krafla Geothermal Field, Iceland, 1. Analysis of Well Test Data. Water Resources Research, 20(11): 1515-1530.

Bodvarsson, G.S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V. and Steingrimsson, B., 1988. A Summary of Modeling Studies of the Nesjavellir Geothermal Field, Iceland, Thirteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 83-91.

Bodvarsson, G.S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V. and Steingrimsson, B., 1990a. The Nesjavellir Geothermal Field, Iceland, Part 1. Field Characteristics and Development of a Three-dimensional Numerical Model. Geothermal Science and Technology, 2(3): 189-228.

Bodvarsson, G.S., Bjornsson, S., Gunnarsson, A., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V. and Steingrimsson, B., 1991. The Nesjavellir Geothermal Field, Iceland, 2. Evaluation of the Generating Capacity of the System. Geothermal Science and Technology, 2(4): 229-261.

Bodvarsson, G.S., Boyle, W., Patterson, R. and Williams, D., 1999. Overview of scientific investigations at Yucca Mountain-the potential repository for high-level nuclear waste. Journal of Contaminant Hydrology, 38(Nos. 1-3): 3-24.

Bodvarsson, G.S., Gislason, G., Gunnlaugsson, E., Sigurdsson, O., Stefansson, V. and Steingrimsson, B., 1993. Accuracy of Reservoir Predictions for the Nesjavellir Geothermal Field, Iceland, Eighteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 273-278.

Bodvarsson, G.S., Pruess, K., Haukwa, C. and Ojiambo, S.B., 1990b. Evaluation of Reservoir Model Predictions for Olkaria East Geothermal Field, Kenya. Geothermics, 19(5): 399-414.

Bodvarsson, G.S., Pruess, K. and Lippmann, M.J., 1986. Modeling of Geothermal Systems. Journal of Petroleum Technology(September): 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. Journal of Geophysical Research, 92(B1): 521-539.

Bodvarsson, G.S., Pruess, K., Stefansson, V., Bjornsson, S. and Ojiambo, S.B., 1987b. East Olkaria Geothermal Field, Kenya, 2. Predictions of Well Performance and Reservoir Depletion. Journal of Geophysical Research, 92(B1): 541-554.

Bodvarsson, G.S., Pruess, K., Stefansson, V. and Eliasson, E.T., 1984b. The Krafla Geothermal Field, Iceland, 2. The Natural State of the System. Water Resources Research, 20(11): 153 -1544.

Bodvarsson, G.S., Pruess, K., Stefansson, V. and Eliasson, E.T., 1984c. The Krafla Geothermal Field, Iceland, 3, The Generating Capacity of the Field. Water Resources Research, 20(11): 1545-1559.

Bullivant, D.P. and O'Sullivan, M.J., 1998. Inverse Modelling of the Wairakei Geothermal Field, LBNL - 41995. In: K. Pruess (Editor), TOUGH Workshop '98, Lawrence Berkeley National Laboratory, Berkeley, California, pp. 53-58.

Buscheck, T.A., 1998. Thermal-Hydrological Models. UCRL-ID-131007, Lawrence Livermore National Laboratory, Livermore, California.

Buscheck, T.A. and Nitao, J.J., 1993. The analysis of repository-heat-driven hydrothermal flow at Yucca Mountain, Fourth High Level Radioactive Waste Management International Conference. American Nuclear Society and American Society of Civil Engineers, Las Vegas, Nevada.

Buscheck, T.A. and Nitao, J.J., 1994. The Impact of Buoyant, Gas-Phase Flow and Heterogeneity on Thermo-Hydrological Behavior at Yucca Mountain, High Level Radioactive Waste Management, Fifth International Conference. American Nuclear Society and American Society of Civil Engineers, Las Vegas, Nevada, pp. 2450-2474.

Butler, S.J., Sanyal, S.K., Henneberger, R.C., Klein, C.W., Gutierrez, H. and De Leon V., J.S., 2000. Numerical modeling of the Cerro Prieto Geothermal Field, Baja California, Mexico, World Geothermal Congress, Beppu and Morioka, Japan.

Carslaw, H.S. and Jaeger, J.C., 1986. Conduction of heat in solids. Oxford University Press, New York, 510 p. pp.

Cho, C.M., 1971. Convective transport of ammonium with nitrification in soil. Can. J. Soil Sci., 51: 339-350.

de Marsily, G., 1986. Quantitative Hydrogeology, Groundwater Hydrology for Engineers. Academic Press, Inc., 440 pp.

Doughty, C., 1999. Investigation of conceptual and numerical approaches for evaluating moisture, gas, chemical, and heat transport in fractured and unsaturated rock. Journal of Contaminant Hydrology, 38: 69-106.

Doughty, C. and Pruess, K., 1992. A Similarity Solution for Two-Phase Water, Air, and Heat Flow Near a Linear Heat Source in a Porous Medium. Journal of Geophysical Research, 97(B2): 1821-1838.

Ehlig-Economides, C.A., Hegeman, P. and Clark, G., 1994. Well Testing-Conclusion: Modern testing meets wide range of objectives. Oil and Gas Journal: 44-47.

Elder, J.W., 1967. Transient Convection in a Porous Medium. Journal of Fluid Mechanics, 27(part 3): 609-623.

Ezzedine, S. and Rubin, Y., 1997. Analysis of the Cape Cod tracer data. Water Resources Research, 33(1): 1-11.

Fabryka-Martin, J.T., Wolfsberg, A.V., Roach, J.L., Winters, S.T. and Wolfsberg, L.E., 1998. Using chloride to trace water movement in the unsaturated zone at Yucca Mountain, Eighth International High-Level Radioactive Waste Management Conference. American Nuclear Society, Las Vegas, NV, pp. 264-268.

Finsterle, S., 1999. ITOUGH2 user's guide. LBL-40040, Lawrence Berkeley National Laboratory.

Fitzgerald, S.D., Wang, C.T. and Pruess, K., 1996. Laboratory and Theoretical Studies of Injection into Horizontal Fractures, 18th New Zealand Geothermal Workshop, pp. 267-273.

Freeze, R.A. and Cherry, J.A., 1979. Groundwater. Prentice-Hall, Inc., 604 pp.

Freyberg, D.L., 1986. A Natural Gradient Experiment on Solute Transport in a Sand Aquifer 2. Spatial Moments and the Advection and Dispersion of Nonreactive Tracers. Water Resources Research, 22(13): 2031-2046.

Garg, S.K. and Pritchett, J.W., 1990. Cold Water Injection Into Single- and Two-Phase Geothermal Reservoir. Water Resources Research, 26(2): 331-338.

Hanano, M., 1992. Reservoir Engineering Studies of the Matsukawa Geothermal Field, Japan. Geothermal Resources Council Transactions, 16(October): 643-650.

Hardin, E.L. and Chestnut, D.A., 1997. Synthesis report on thermally driven coupled processes. UCRL-ID-128495, Lawrence Livermore National Laboratory, Livermore, CA.

Haukwa, C.B., Wu, Y.-S. and Bodvarsson, G.S., 1999. Thermal loading studies using the Yucca Mountain unsaturated zone model. Journal of Contaminant Hydrology, 38: 217-255.

Hayba, D.O. and Ingebritsen, S.E., 1997. Multiphase groundwater flow near cooling plutons. Journal of Geophysical Research, 102(B6): 12,235-12,152.

Henry, H.R., 1964. Effects of dispersion on salt encroachment in coastal aquifers. 1613-C, U.S. Geological Survey Water Supply Paper.

Herkelrath, W.N., Moench, A.F. and O'Neal II, C.F., 1983. Laboratory investigations of steam flow in a porous medium. Water Resources Research, 19: 931-937.

Hunt, T.M., Allis, R.G., Blakeley, M.R. and O'Sullivan, M.J., 1990. Testing Reservoir Simulation Models for the Broadlands Geothermal Field using Precision Gravity Data. Geothermal Resources Council Transactions, 14, Part II(August): 1287-1294.

Ingebritsen, S.E. and Sorey, M.L., 1988. Vapor-Dominated Zones Within Hydrothermal Systems: Evolution and Natural State. Journal of Geophysical Research, 93(B11): 13,635-13,655.

Javandel, I., Doughty, C. and Tsang, C.F., 1984. Groundwater Transport: Handbook of Mathematical Models. American Geophysical Union, Washington, D.C., 228 pp.

Kabir, C.S. and Hasan, A.R., 1986. Prefracture Testing in Tight Gas Reservoirs. SPEFE: 128-138.

Kruger, P. and Ramey, H.J., 1974. Stimulation and Reservoir Engineering of Geothermal Resources. SGR-TR-1, Stanford University, Stanford, CA.

Kuchuk, F.J., 1995. Well Testing and Interpretation for Horizontal Wells. Journal of Petroleum Technology: 36-41.

Lai, C.H., Bodvarsson, G.S. and Witherspoon, P.A., 1985. Numerical Studies of Silica Precipitation/Dissolution, Tenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 279-286.

Lam, S.T., Hunsbedt, A., Kruger, P. and Pruess, K., 1988. Analysis of the Stanford Geothermal Reservoir Model Experiments Using the LBL Reservoir Simulator. Geothermics, 17(4): 595-605.

LeBlanc, D.R., Garabedian, S.P., Hess, K.M., Gelhar, L.W., Quadri, R.D., Stollenwerk, K.G. and Wood, W.W., 1991. Large-scale Natural Gradient Tracer Test in Sand and Gravel, Cape Cod, Massachusetts 1. Experimental design and Observed Tracer Movement. Water Resources Research, 27(5): 895-910.

Lin, W., Wilder, D., Blair, S., Daily, W., Gdowski, G., Glassley, W., Lee, K., Meike, A., Ramirez, A., Roberts, J., Ruddle, D., Wagoner, J., Watwood, D., Williams, T. and Carlson, R., 1998. The Large Block Test of the Exploratory Studies Facility Thermal Tests, High Level Radioactive Waste Management, Eighth International Conference. American Nuclear Society, Las Vegas, NV, pp. 49-51.

Mackay, D.M., Freyberg, D.L. and Roberts, P.V., 1986. A Natural Gradient Experiment on Solute Transport in a Sand Aquifer 1. Approach and Overview of Plume Movement. Water Resources Research, 22(13): 2017-2029.

Malate, R.C.M. and O'Sullivan, M.J., 1992. Mathematical modeling of non-isothermal silica transport and deposition in a porous medium. Geothermics, 21(4): 519-544.

Mangold, D.C. and Tsang, C.F., 1983. A Study of Nonisothermal Chemical Transport in Geothermal Systems by a Three-Dimensional Coupled Thermal and Hydrologic Parcel Model. Geothermal Resources Council, Transactions, 7: 455-459.

McNab, W.W. and Narasimhan, T.N., 1993. A multiple species transport model with sequential decay interactions in heterogeneous subsurface environments. Water Resources Research, 29(8): 2737-2746.

Menzies, A.J., Granados, E.E., Sanyal, S.K., Merida-I, L. and Caicedo-A, A., 1991. Numerical Modeling of the Initial State and Matching of Well Test Data from the Zunil Geothermal Field, Guatemala, Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 193-210.

Menzies, A.J. and Pham, M., 1995. A field-wide numerical simulation model of The Geysers Geothermal Field, California, USA, World Geothermal Congress, Florence, Italy, pp. 1697-1702.

Menzies, A.J., Sanyal, S.K., Granados, E.E., Pham, M., Lima, E., Cuevas, A. and Torres, J., 1996. Analysis of Well Test Data from the High-Temperature Geothermal System of Amatitlan, Guatemala. Geothermal Resources Council Transactions, 20(September/October): 821-827.

Moore, J.N. and Adams, M.C., 1988. Use of Fluid Inclusion Studies in Geothermal Exploration and Reservoir Characterization. In: M.J. Lippmann (Editor), Proceedings of the Technical Review on Advances in Geothermal Reservoir Technology-Research in Progress, Lawrence Berkeley Laboratory, Berkeley, California, pp. 19-22.

Moore, J.N., Hulen, J.B., Lemieux, M.M., Sternfield, J.N. and Walters, M.A., 1989. Petrographic and Fluid Inclusion Evidence for Past Boiling, Brecciation, and Associated Hydrothermal Alteration above the Northwest Geysers Steam Field, California. Geothermal Resources Council, TRANSACTIONS, 13: pp, 467-472.

Moridis, G.J. and Pruess, K., 1992. TOUGH Simulations of Updegraff's Set of Fluid and Heat Flow Problems. LBL-32611, UC-800, Lawrence Berkeley Laboratory, Berkeley, CA.

National Resource Council, 1990. Ground Water Models Scientific and Regulatory Applications. National Academy Press, Washington D.C., 303 pp.

Nishi, Y., Ishido, T. and Matsushima, N., 1998. The Geothermal System in Aogashima Volcano Based Upon Self-Potential Data and Numerical Simulation. Geothermal Resources Council Transactions, 22(September 20-23): 471-475.

Nitao, J.J., 1988. Numerical Modeling of the Thermal and Hydrological Environment Around a Nuclear Waste Package Using the Equivalent Continuum Approximation: Horizontal Emplacement. UCID - 21444, Lawrence Livermore National Laboratory, Livermore, California.

Nitao, J.J., Buscheck, T.A. and Chestnut, D.A., 1992. The Implications of Episodic Nonequilibrium Fracture-Matrix Flow on Site Suitability and Total System Performance, Third High Level Radioactive Waste Management International Conference. American Nuclear Society and American Society of Civil Engineers, Las Vegas, Nevada.

O'Sullivan, M.J., 1981. A Similarity Method for Geothermal Well Test Analysis. Water Resources Research, 17(2): 390-398.

O'Sullivan, M.J., 1985. Geothermal reservoir simulation. Energy Research, 9: 313-332.

O'Sullivan, M.J., Barnett, B.G. and Razali, M.Y., 1990. Numerical Simulation of the Kamojang Geothermal Field, Indonesia. Geothermal Resources Council Transactions, 14, Part II(August): 1317-1324.

O'Sullivan, M.J., Bullivant, D.P., Follows, S.E. and Mannington, W.I., 1998. Modelling of the Wairakei-Tauhara Geothermal System, LBNL - 41995. In: K. Pruess (Editor), TOUGH Workshop '98, Lawrence Berkeley National Laboratory, Berkeley, California, pp. 1-6.

O'Sullivan, M.J., Pruess, K. and Lippmann, M., 2001. State of the art of geothermal reservoir simulation. Geothermics, 30(4).

Oldenburg, C.M. and Pruess, K., 1993. A Two-Dimensional Dispersion Module for the TOUGH2 Simulator. LBL-32505, UC-250, Lawrence Berkeley National Laboratory, Berkeley, CA.

Oldenburg, C.M. and Pruess, K., 1995a. Dispersive transport dynamics in a strongly coupled groundwater-brine flow system. Water Resources Research, 31(2): 289-302.

Oldenburg, C.M. and Pruess, K., 1995b. EOS7R: Radionuclide Transport for TOUGH2. LBL-34868, UC-800, Lawrence Berkeley National Laboratory, Berkeley, CA.

Oreskes, N., Shrader-Frechette, K. and Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the earth sciences, Science, pp. 641-646.

Pham, M. and Menzies, A.J., 1993. Results from a Field-Wide Numerical Model of the Geysers Geothermal Field, California. Geothermal Resources Council Transactions, 17(October): 259-265.

Pham, M., Menzies, A.J., Sanyal, S.K., Lima, E., Shimida, K., Juarez, J. and Cuevas, A., 1996. Numerical Modeling of the High-Temperature Geothermal System of Amatitlan, Guatemala. Geothermal Resources Council Transactions, 20(September/October): 833-838.

Pham, M., Sanyal, S.K., Menzies, A.J., Naka, T., Takeuchi, R. and Iwata, S., 1995. Numerical Modeling of the High-Temperature Two-Phase Reservoir at Uenotai Geothermal Field, Akita Prefecture, Japan, World Geothermal Congress, 1995. International Geothermal Association, Florence, Italy, pp. 1703-1707.

Philip, J.R., 1955. Numerical Solutions of Equations of the Diffusion Type with Diffusivity Concentration Dependent. Trans. Faraday Soc., 51: 885-892.

Pritchett, J.W., 1995. A Numerical Simulation of the Oguni Geothermal Field. Geothermal Resources Council Transactions, 19(October): 529-537.

Pritchett, J.W., Garg, S.K., Ariki, K. and Kawano, Y., 1991. Numerical Simulation of the Sumikawa Geothermal Field in the Natural State, Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 151-158.

Pruess, K., 1990. Modeling of Geothermal Reservoirs: Fundamental Processes, Computer Simulation and Field Applications. Geothermics, 19(1): 3-15.

Pruess, K., 1991. TOUGH2 - A General-Purpose Numerical Simulator for Multiphase Fluid and Heat Flow. LBL-29400, Lawrence Berkeley Laboratory, Berkeley, California.

Pruess, K., Bodvarsson, G.S., Stefansson, V. and Eliasson, E.T., 1984a. The Krafla Geothermal Field, Iceland, 4. History Match and Prediction of Individual Well Performance. Water Resources Research, 20(11): 1561-1584.

Pruess, K., Oldenburg, C. and Moridis, G., 1998. Overview of TOUGH2, Version 2.0, LBNL - 41995. In: K. Pruess (Editor), TOUGH Workshop '98, Lawrence Berkeley National Laboratory, Berkeley, California, pp. 307-314.

Pruess, K., Simmons, A., Wu, Y.S. and Moridis, G., 1996. TOUGH2 Software Qualification. LBL-38383, UC-814, Lawrence Berkeley National Laboratory, Berkeley, California.

Pruess, K. and Tsang, Y., 1994. Thermal Modeling for a Potential High-Level Nuclear Waste Repository at Yucca Mountain, Nevada. LBL - 35381, UC - 600, University of California, Lawrence Berkeley Laboratory, Berkeley, CA.

Pruess, K., Tsang, Y.W. and Wang, J.S.Y., 1984b. Numerical Studies of Fluid and Heat Flow Near High-Level Nuclear Waste Packages Emplaced in Partially Saturated Fractured Tuff. LBL - 18552, Lawrence Berkeley Laboratory, Berkeley, California.

Pruess, K., Wang, J.S.Y. and Tsang, Y.W., 1990a. On Thermohydrologic Conditions Near High-Level Nuclear Wastes Emplaced in Partially Saturated Fractured Tuff 1. Simulation Studies With Explicit Consideration of Fracture Effects. Water Resources Research, 26(6): 1235-1248.

Pruess, K., Wang, J.S.Y. and Tsang, Y.W., 1990b. On Thermohydrologic Conditions Near High-Level Nuclear Wastes Emplaced in Partially Saturated Fractured Tuff, Part 2. Effective Continuum Approximation. Water Resources Research, 26(6): 1249-1261.

Reda, D.C., 1984. Natural convection experiments about a finite-length cylindrical heat source in a liquid-saturated porous medium. SAND83-2209C, Sandia National Laboratories, Albuquerque, NM.

Robertson-Tait, A., Klien, C.W., McNitt, J.R., Naka, T., Takeuchi, R., Iwata, S., Saeki, Y. and Inoue, T., 1990. Heat source and fluid migration concepts at the Uenotai Geothremal Field, Akita Prefecture, Japan. Geothermal Resources Council, Transactions, 14, PART II(August): 1325-1331.

Shan, C. and Stephens, D.B., 1995. An analytical solution for vertical transport of volatile chemicals in the vadose zone. Journal of Contaminant Hydrology, 18: 259-277.

Shanyan, A. and Wong, D., 1998. Well testing information and its use in shallow reservoir management. Journal of Canadian Petroleum Technology, 37(3): 55-62.

Sonnenthal, E., Spycher, N., Apps, J. and Simmons, A., 1998. Thermo-Hydro-Chemical Predictive Analysis for the Drift-Scale Heater Test. Level 4 Milestone SPY289M4, Lawrence Berkeley National Laboratory, Berkeley, California.

Stanford Geothermal Program, 1980. Proceedings Special Panel on Geothermal Model Intercomparison Study, Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

Steingrimsson, B., Bodvarsson, G.S., Gunnlaugsson, E., Gislason, G. and Sigurdsson, O., 2000. Modeling Studies of the Nesjavellir Geothermal Field, Iceland. In: E. Iglesias et al. (Editors), World Geothermal Congress 2000. International Geothermal Association and Japanese Organizing Committee for WGC 2000, Kyushu-Tohuku, Japan, pp. 2899-2904.

Sudicky, E.O. and Frind, E.O., 1982. Contaminant transport in fractured porous media: analytical solutions for a system of parallel fractures. Water Resources Research, 18(6): 1634-1642.

Sudicky, E.O., Gilgam, R.W. and Frind, E.O., 1985. Experimental investigation of solute transport in stratified porous media, 1. The nonreactive case. Water Resources Research, 21(7): 1035-1041.

Theirrin, J. and Kitanidis, P., 1994. Solute dilution at the Borden and Cape Cod groundwater tracer tests. Water Resources Research, 30(11): 2883-2890.

Thompson, L.G. and Reynolds, A.C., 1997. Well testing for radially heterogeneous reservoirs under single and multiphase flow conditions. SPE Formation Evaluation: 57-64.

Tsang, Y.W., Apps, J., Birkholzer, J.T., Freifeld, B., Hu, M.Q., Peterson, J., Sonnenthal, E. and Spycher, N., 1999a. Yucca Mountain Single Heater Test Final Report. LBNL-42537, Lawrence Berkeley National Laboratory, Berkeley, California.

Tsang, Y.W., Apps, J., Birkholzer, J.T., Peterson, J.E., Sonnenthal, E., Spycher, N. and Williams, K.H., 1999b. Yucca Mountain Drift Scale Test Progress Report. LBNL-42538, Lawrence Berkeley National Laboratory, Berkeley, California.

Tsang, Y.W. and Birkholzer, J.T., 1999. Predictions and observations of the Thermal-hydrological conditions in the Single Heater Test. Journal of Contaminant Hydrology, 38(Nos. 1-3): 385-425.

Tsang, Y.W. and Pruess, K., 1987. A Study of Thermally Induced Convection Near a High-Level Nuclear Waste Repository in Partially Saturated Fractured Tuff. Water Resources Research, 23(10): 1958-1966.

Tsang, Y.W. and Pruess, K., 1989. Preliminary Studies of Gas Phase Flow Effects and Moisture Migration at Yucca Mountain, Nevada. LBL - 28819, Lawrence Berkeley Laboratory, Berkeley, California.

Tsang, Y.W. and Pruess, K., 1990. Further Modeling Studies of Gas Movement and Moisture Migration at Yucca Mountain, Nevada. LBL - 29127, Lawrence Berkeley Laboratory, Berkeley, California.

Tulinius, H. and Sigurdsson, O., 1989. Two-dimensional Simulation of the Krafla-Hvitholar Geothermal Field, Iceland, Fourteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 87-93.

van Genuchten, M.T., 1985. Convective-dispersive transport of solutes involved in sequential first-order decay reactions. Computers and Geosciences, 11(2): 129-147.

Vauclin, A.K., Khanji, D. and Vacchaud, G., 1979. Experimental and numerical study of a transient, two-dimensional unsaturated-saturated water table recharge problem. Water Resources Research, 15(5): 1089-1101.

White, S.P., 1995. Reaction and Transport of Chemicals in a Two Phase Geothermal Reservoir, World Geothermal Congress, 1995. International Geothermal Association, Florence, Italy, pp. 1599-1604.

White, S.P., 1997. Including Chemical Transport and Reaction in Numerical Geothermal Reservoir Models. Geothermal Resources Council, Transactions, 21: 595-600.

White, S.P. and Mroczek, E.K., 1998. Permeability Changes During the Evolution of a Geothermal Field Due to the Dissolution and Precipitation of Quartz. Transport in Porous Media, 33: 81-101.

Williamson, K.H., 1990. Reservoir Simulation of the Geysers Geothermal Field, Fifteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, pp. 113-123.

Williamson, K.H., 1992. Development of a Reservoir Model for The Geysers Geothermal Field. In: C. Stone (Editor), Monograph on the Geysers Geothermal Field, Special Report No. 17. Geothermal Resources Council, Davis, CA, pp. 179-187.

Wu, Y.-S., Haukwa, C. and Bodvarsson, G.S., 1999. A site-scale model for fluid and heat flow in the unsaturated zone of Yucca Mountain, Nevada. Journal of Contaminant Hydrology, 38(Nos. 1-3): 185-215.

Wu, Y.-S. and Pruess, K., 2000. Numerical simulation of non-isothermal multiphase tracer transport in heterogeneous fractured porous media. Advances in Water Resources, 23: 699-723.

Xu, T., Pruess, K. and Brimhall, G., 1998. An Improved Equilibrium Kinetics Speciation Algorithm for Redox Reactions in Variably Saturated Subsurface Flow Systems. LBNL-41789, Lawrence Berkeley National Laboratory, Berkeley, CA.

Yang, I.C., Rattray, G.W. and Scofield, K.M., 1998. Carbon and hydrogen isotopic compositions for pore water extracted from cores at Yucca Mountain, Nevada, Eighth International High-Level Radioactive Waste Management Conference. American Nuclear Society, Las Vegas, NV, pp. 27-32.

Zhang, K., Wu, Y.-S., Ding, C. and Pruess, K., 2001. Application of parallel computing to a large-scale reservoir simulation, Twenty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Table 1. Anthropogenic thermal and geothermal–modeling efforts.

(1) Site	**(2) Conditions, Phases**	**(3) Code**	**(4) Number of Dimensions**	**(6) Physical Volume Modeled**	**(7) Number of Model Elements or Gridblocks**	**(8) Calibration Method [a]**	**(9) Length of Prediction Period**	**(10) Calibration Inferences**	**(11) Reference**
Yucca Mountain, USA	1,2	TOUGH2*, NUFT	up to 3	~26 km^3, 60 layers	up to 10^6	NS, T, Moisture saturation	10,000 years		(Buscheck, 1998; Wu et al., 1999)
Wairakei–Tauhara, New Zealand	2 phase	TOUGH2*	3	12 layers	1,417	NS, T, HM P,T, w/ inverse modeling		More layers required	(Bullivant and O'Sullivan, 1998; O'Sullivan et al., 1998)
Geysers, USA	vapor dominated	Proprietary Code dual permeability	3	600 km^3	2,880	HM (30 years)	20 years	Permeability barriers and enhanced permeability regions	(Williamson, 1990)
		TETRAD, dual porosity	3	600 km^3	2,880	HM (30 years production)	2 scenarios, 20 years	not possible to create initial state model with boiling fluid below –8000 ft msl	(Pham and Menzies, 1993)
Cerro Prieto, Mexico	1,2	TOUGH2*	3		347	NS, HM, P, T, many wells	2 Scenarios, 30 years	location of upflow	(Antunez et al., 1991)
Nesjavellir, Iceland	2 phase, 18 wells, flow testing, reservoir studies	TOUGH2*	3	288 km^3	300	NS (100k years), HM (4 years)	30 years	location of upflow zone	(Bodvarsson et al., 1988; Bodvarsson et al., 1993) (Bodvarsson et al., 1990a; Bodvarsson et al., 1991)

[a] **NS – Natural State, HM, – History Matching, T – Temperature, P – Pressure**

*** includes earlier and modified versions**

(1) Site	(2) Conditions, Phases	(3) Code	(4) Number of Dimensions	(6) Physical Volume Modeled	(7) Number of Model Elements or Gridblocks	(8) Calibration Method [a]	(9) Length of Prediction Period	(10) Calibration Inferences	(11) Reference
Monteverdi Zone, Larderello, Italy	vapor dominated	STAR*	3	75 km^3	480	NS, 2 transient production tests	20 years		(Bertani and Cappetti, 1995)
Kamojang, Indonesia	vapor dominated	TOUGH2*	3		a)456 b) 570	NS, P (20,000,000 years) HM, P (7 years)	30 years		(O'Sullivan et al., 1990)
East Olkaria, Kenya	2 phase	TOUGH2*	3	3 layers	150	HM, flow rate and enthalpy data, 6.5 years		high permeabilty region	(Bodvarsson et al., 1990b; Bodvarsson et al., 1987a; Bodvarsson et al., 1987b; Pham et al., 1996)
		TOUGH2*	3	8 x 12 km, 3 layers	252		Many scenarios, 30 years		(Bodvarsson et al., 1990b; Bodvarsson et al., 1987a; Bodvarsson et al., 1987b; Pham et al., 1996)
Krafla, Iceland	2 phase	TOUGH2*	1, 2, quasi–3	100 blocks each 1 – $8x10^4$ m^3	100	Well test data, NS, T, P (20,000 years), HM	8 – 30 years with caution		(Bodvarsson et al., 1984a; Bodvarsson et al., 1984b; Bodvarsson et al., 1984c)

a **NS – Natural State, HM, – History Matching, T – Temperature, P – Pressure**
*** includes earlier and modified versions**

(1) Site	(2) Conditions, Phases	(3) Code	(4) Number of Dimensions	(6) Physical Volume Modeled	(7) Number of Model Elements or Gridblocks	(8) Calibration Method [a]	(9) Length of Prediction Period	(10) Calibration Inferences	(11) Reference
Cove Fort Sulphurdale, US	1,2		3	0.5 km^3, 5 layers	2,000	HM	13 years for tracer test		(Bloomfield et al., 1998)
Krafla–Hvitholar, Iceland	1,2	TOUGH2*	2		85	NS, 3 Wells, T, P	3 Scenarios, 10 years	importance of fault	(Tulinius and Sigurdsson, 1989)
Matsukawa, Japan	1,2	Not Mentioned	2		375	NS, (50,000 years)			(Hanano, 1992)
Oguni, Japan	1,2	NIGHTS (liquid), STAR* (liquid, steam)	3		2,878	NS (250,000 years), Current State, T, P	30 years		(Pritchett, 1995)
Sumikawa, Japan	1,2	STAR*	3		1,440	NS (30,000 years), T, P	50 years		(Pritchett et al., 1991)
Amatitlan, Guatemala	2 phase	TOUGH2*	3	140 km^3, 5 layers	1,220	NS T, P, HM (well flow testing ~30 days)	30 years with caution		(Pham et al., 1996)
Zunil, Guatemala	vapor dominated	TOUGH2*	3	16 km^3	459	NS, T,P, well test data, interference test		secondary upflow zone	(Menzies et al., 1991)
Uenotai, Japan	liquid dominated with two–phase region	Not Disclosed	3	80 km^3	358	NS, HM, many wells	30 years	recharge locations and amounts, low permeability zones, flow direction	(Antunez et al., 1990)
		Not Disclosed	3	80 km^2, 4 layers	557	NS (few 10,000 years), HM flow test, interference test (3 mo, 1 year)	35 years	location of sinks, sources	(Pham et al., 1995)

[a] **NS – Natural State, HM, – History Matching, T – Temperature, P – Pressure**

*** includes earlier and modified versions**

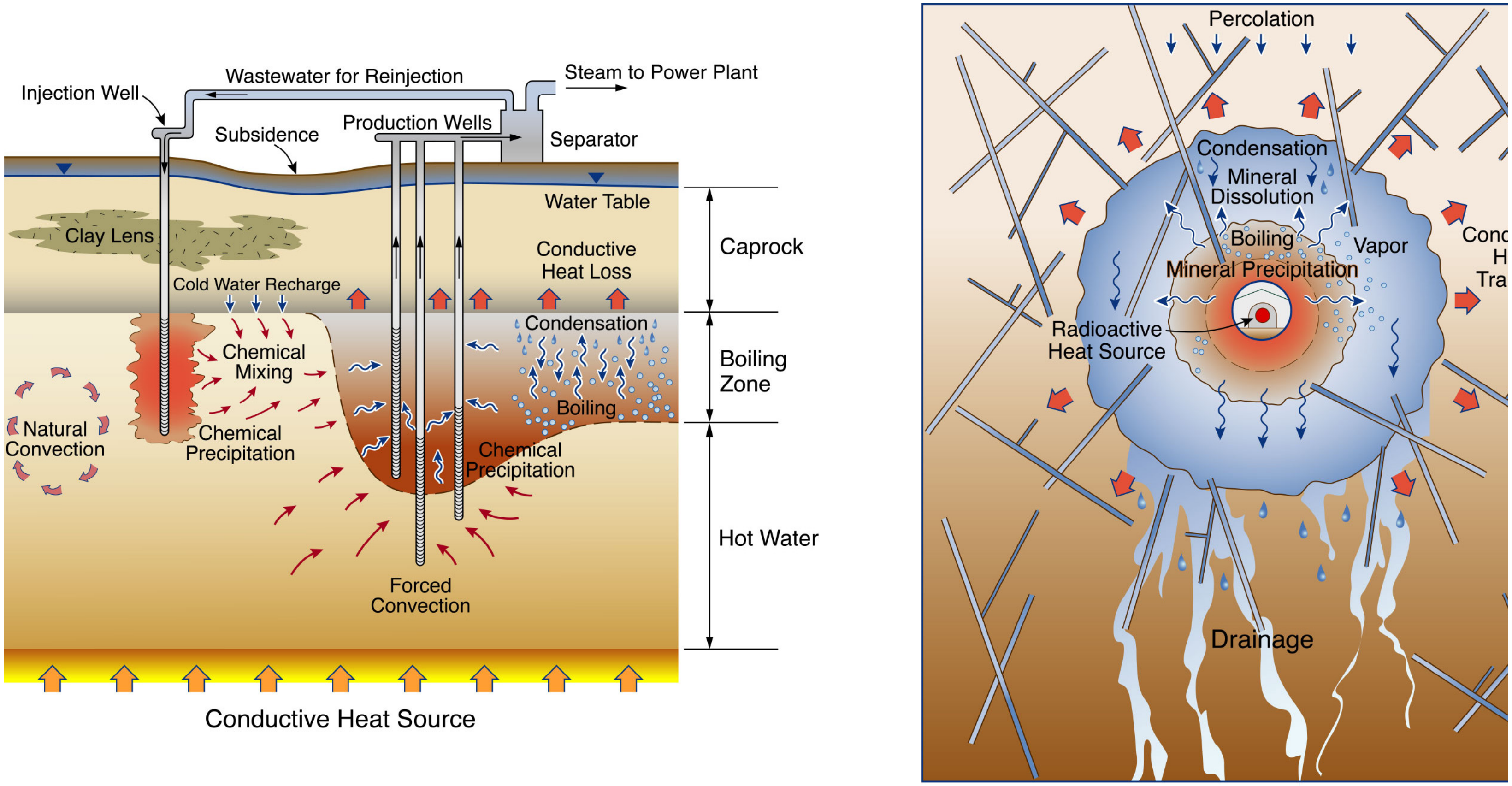

Figure 1. Geothermal (left) and AT (right) processes including conductive and convective heat transfer, advection of fluids, boiling, condensation, mineral dissolution and precipitation, and solute transport (left adapted from Bodvarsson and Witherspoon (1989), right adapted from Bodvarsson et al. (2000)).

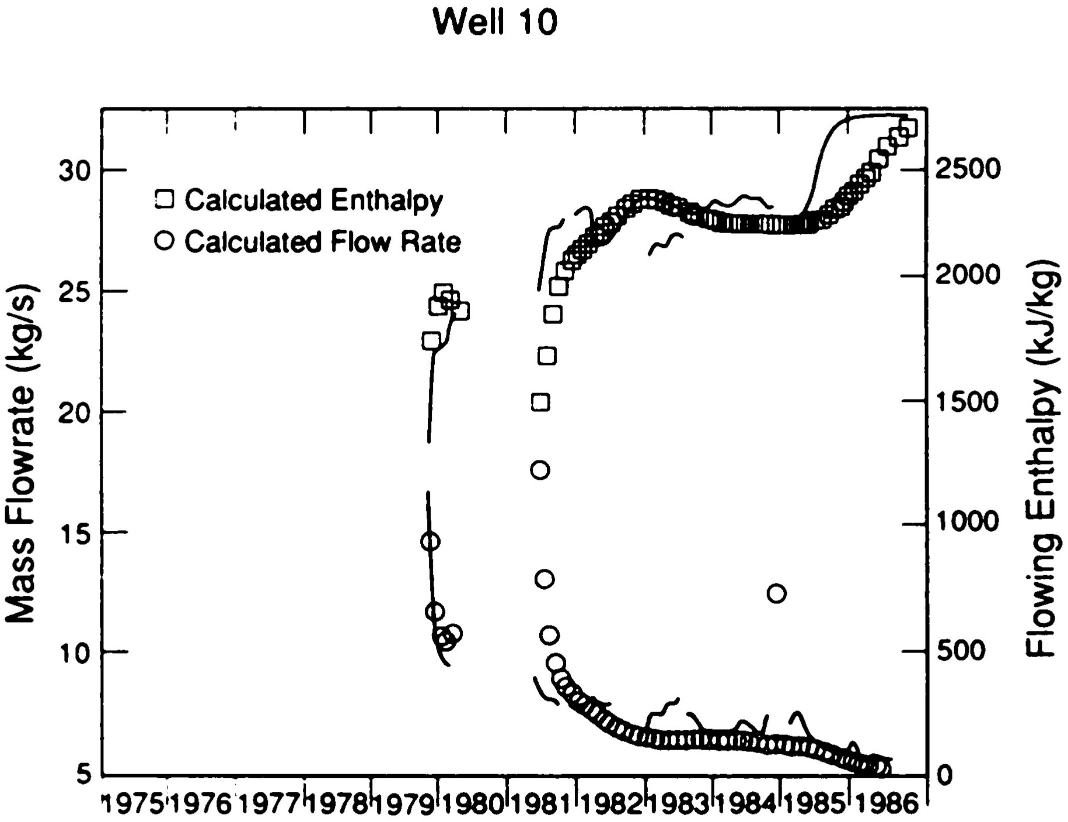

Figure 2. Comparison between predicted and observed flow rates and enthalpies from 1984-1987 for well 10 at Olkaria East. (from Bodvarsson et al. 1990b)

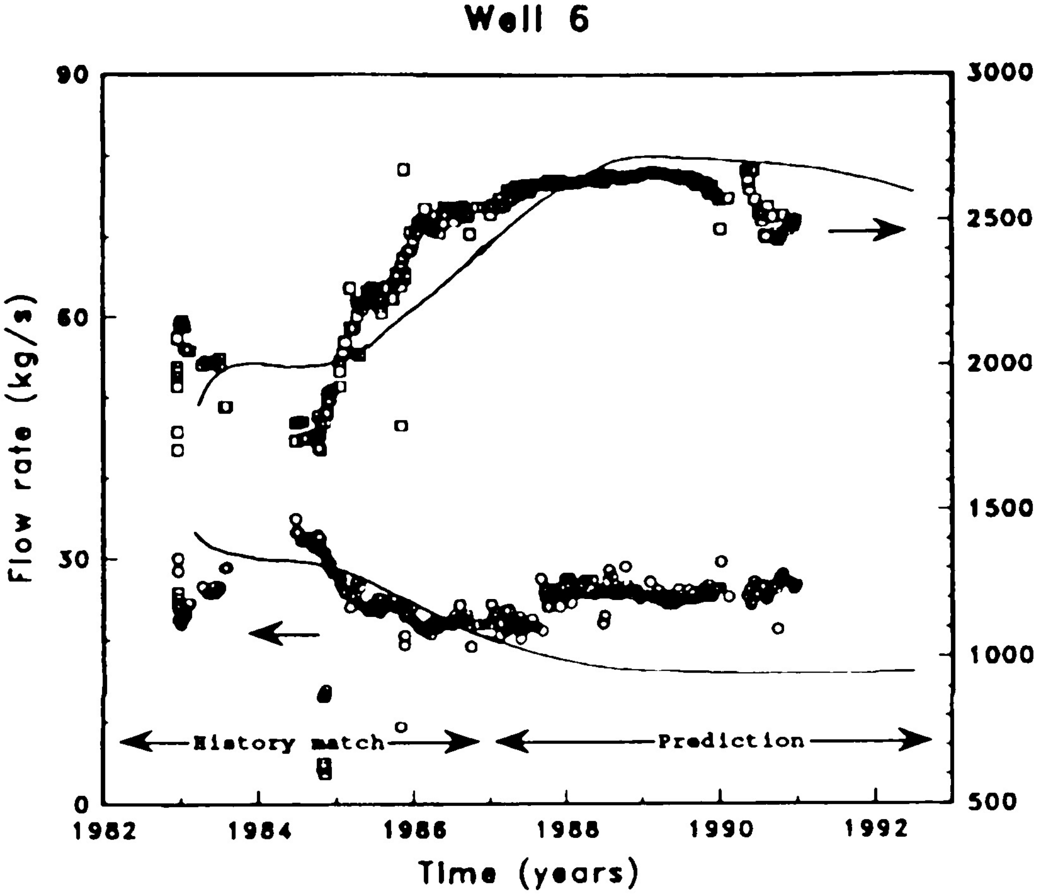

Figure 3. Comparison between predicted and observed flowrates and enthalpies for well 6 at Nesjavellir. (from Bodvarsson et al. 1993)

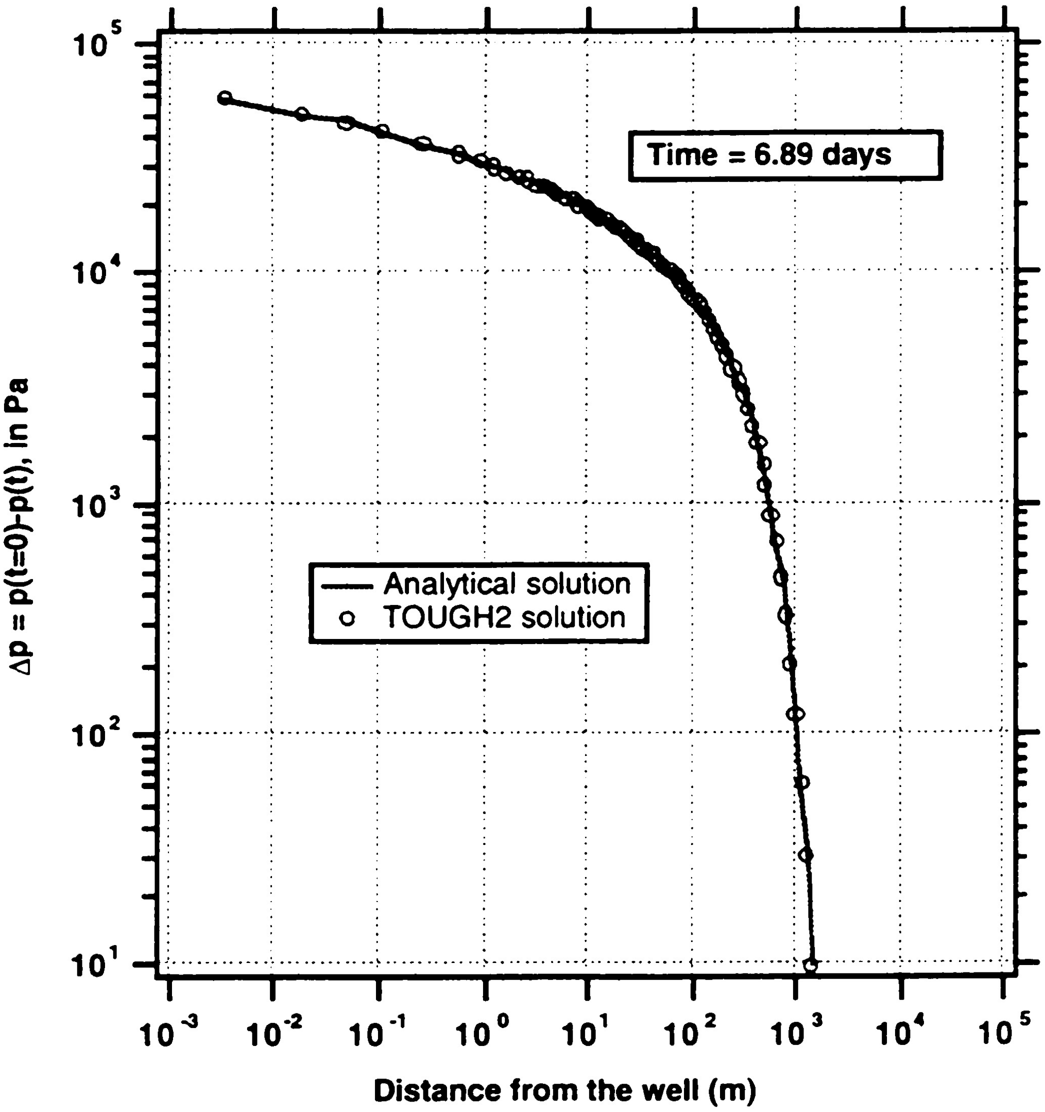

Figure 4. Comparison of analytical and simulation results for pressure drawdown for one-dimensional radial flow from a well in an infinite gas reservoir. (from Pruess et al., 1996)

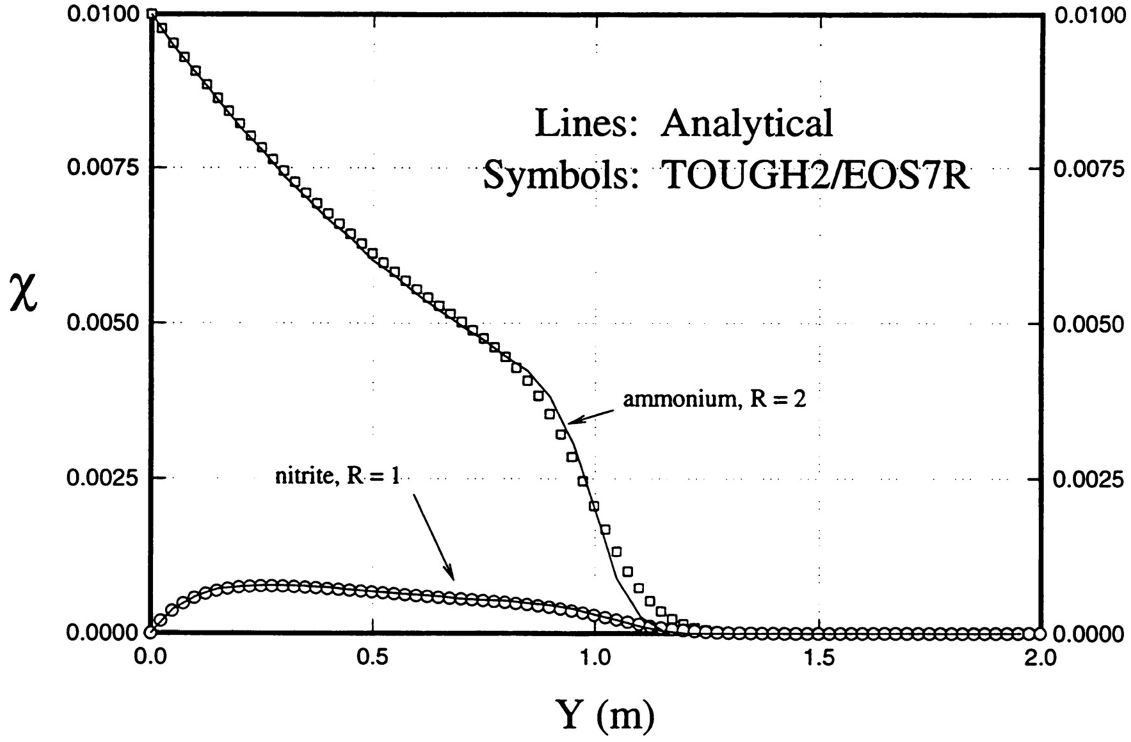

Figure 5. Comparison of analytical and simulation results for the reactive transport of ammonium with oxidation to nitrite. Ammonium and nitrite values are mole fractions. (from Oldenburg and Pruess, 1995b)

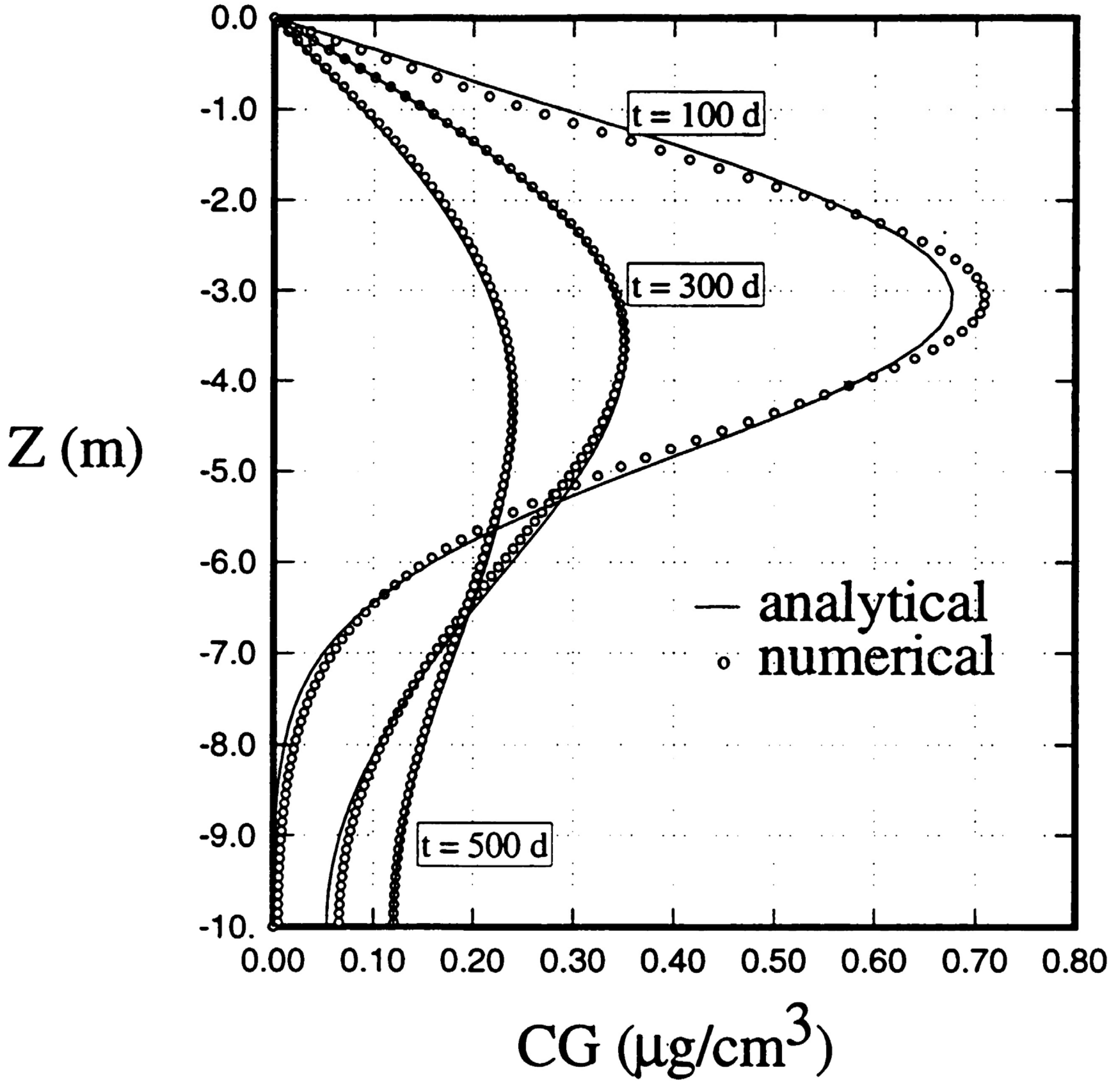

Figure 6. Comparison of analytical and numerical results of infiltrating water passing through a uniform vadose zone containing a region having a partially soluble, volatile chemical considering advection, diffusion, dissolution, volatilization, and sorption. CG is concentration in the gas. (from Oldenburg and Pruess, 1995b)

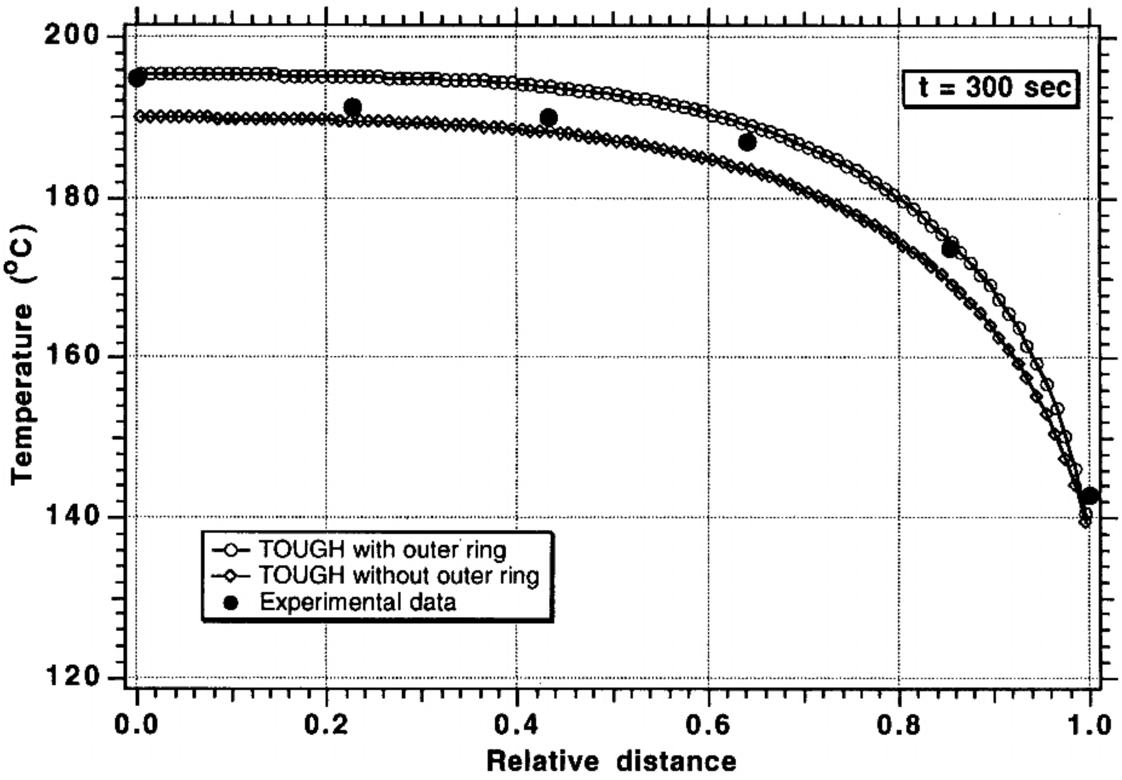

Figure 7. Comparison of experimental and simulation results for the temperature profile in a boiling core. (from Moridis and Pruess, 1992)