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NUMERICAL EVALUATION OF GEOTHERMAL SYSTEMS

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In the last few years the geothermal group of the Lawrence Berkeley Laboratory has developed comprehensive expertise in numerical modeling of geothermal systems. We have carried out detailed simulations of various fields in the U.S.A. (Baca, New Mexico; Heber, California); Mexico)(Cerro Prietro); Iceland (Krafla); and Kenya (Olkaria). These simulation studies have illustrated the usefulness of numerical models for the overall evaluation of geothermal systmems. The methology for modeling the behavior of geothermal systems, different approaches to geothermal reservoir modeling and how they can be applied in comprehensive evaluation work are discussed.

Nos últimos anos o grupo de geotermia do laboratório Lawrence Berkeley desenvolveu grande habilidade no modelamento de sistemas geotérmicos. Nós realizamos simulações detalhadas de vários campos nos Estados Unidos (Baca, Novo México; Heber, Califórnia); México (Cerro Prieto); Islândia (Krafla); e Quênia (Olkaria). Estes estudos de simulação têm ilustrado a utilidade dos modelos numéricos para a avaliação de sistemas geotérmicos como um todo. A metodologia para o modelamento do comportamento de sistemas geotérmicos, diferentes formas de modelamento de reservatórios geotérmicos e como elas podem ser aplicadas em um trabalho de avaliação, são discutidas neste trabalho.

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INTRODUCTION

Geothermal systems are generally very complex, exhibiting such features as fracture-dominated flow, change, chemical reactions and thermal effects. In order to accurately analyze data from geothermal wells and estimate the generating potential of a system, modeling studies must be carried out. When a model of a geothermal system is developed, the existing field data must be carefully evaluated, and the important physical processes that occur in the system identified. After a plausible conceptual model of the field is developed, one must choose a mathematical (numerical) model that can realistically evaluate the performance of the geothermal reservoir, and reliably predict its future behavior.

Modeling the natural state of a field prior to the simulation of the system under exploitation can give very valuable reservoir information. It not only tests qualitatively the conceptual model, but also gives estimates of mass and heat flow in the system. Furthermore, it provides consistent initial conditions for the exploitation models.

The primary objectives for geothermal reservoir modeling are to provide answers to important reservoir management questions, relating to well decline, well spacing, generating capacity (power potential) of the reservoir, injection effects, and potential subsidence and scaling problems. These questions must be addressed using a proper exploitation model that has evolved from the conceptual model and the natural state modeling studies.

A brief review of geothermal reservoir modeling, emphasizing recent developments, is presented here. The different modeling approaches are described and their advantages and limitations are discussed. Examples are given to illustrate the different methodologies for modeling of natural state, exploitation, injection and multicomponent flow. Earlier summaries of geothermal reservoir modeling are given by Witherspoon et al. (1977), Grant (1983), and O'Sullivan (1985).

PHYSICAL PROCESSES AND CONCEPTUAL MODELS

As opposed to oil and gas reservoirs, geothermal systems are very dynamic in their natural state (Donald-

son et al., 1983). There is continuous transport of fluid, heat and chemical species. Important physical processes in geothermal systems, most of them strongly coupled, include mass transport, convective and conductive heat transfer, phase change (boiling and condensation), dissolution and precipitation of minerals, and stress change due to pore pressure changes.

In modeling geothermal reservoirs one must carefully evaluate which processes need to be considered in a specific modeling study (Witherspoon et al., 1977). This will depend upon the objectives of the study and the complexity of the geothermal system. Most presently available geothermal simulators only consider single-component mass and heat transport. In recent years several simulators capable of modeling the transport of a second component, either a noncondensible gas or a dissolved solid, have been developed.

A good conceptual model is one which considers all of the important properties and process that affect the behavior of the system and represents the current knowledge of the geothermal system and its dynamics. It serves as a starting point for resource assessment.

MODELING METHODS

There are presently three methods available for modeling the behavior of geothermal reservoirs. They are decline curve analysis, lumped-parameter methods and distributed parameter methods (Grant, 1983). Each method is described briefly below.

Decline curve analysis

Decline curve analysis is used to predict future well decline by fitting algebraic equations to observed flow rate decline data from wells (Zais & Bodvarsson, 1980). The predicted flow decline can then be used to estimate the number of make-up (additional) wells that will be needed in the future. Various functional forms have been suggested in the literature, including exponential, hyperbolic and harmonic expressions.

Decline curves have been used with some success for vapor dominated systems (Budd, 1972; Stockton et al., 1984); much less experience is available for hot water reservoirs. Major problems with decline curve analysis are the lack of a sound theoretical basis and the fact that they cannot take into account changes in field operation (e.g., infill drilling, injection) (Grant et al., 1982).

Lumped-parameter models

For the sake of tradition, we will discuss lumped- and distributed-parameter models separately, although basically lumped-parameter models are simply distributed-parameter models with a coarse sptial discretization.

Most lumped-parameter models use two blocks to represent the entire system. One of the blocks represents the main reservoir (or the welfield) and the other acts as a recharge block. The governing equations for these models can often be reduced to ordinary differential equations that can be solved semi-analytically. Lumped-parameter models are generally calibrated against a pressure history and the average enthalpy of the produced fluids. After obtaining a history match, the model is used to predict future average reservoir pressure and fluid enthalpy.

The main advantages of the lumped-parameter models are their simplicity and the fact that they do not require the use of large computers. Some of the disadvantages are:

(1) They do no consider fluid flow within the reservoir and neglect spatial variations in thermodynamic conditions and reservoir properties.
(2) They cannot match well the average enthalpy and noncondensible gas content of the produced fluids because of the large grid block sizes.
(3) They cannot simulate fronts such as phase or thermal fronts due to the coarse space discretization.
(4) They cannot consider questions of well spacing or injection well locations.

Distributed-parameter models

Distributed-parameter models are very general models that can be used to simulate reservoirs with few (equivalent to lumped-parameter models) or many (> 100 - 1000) grid blocks. They can be used to simulate the entire geothermal system, including reservoir, caprock, bedrock, shallow cold aquifers, recharge zones, etc. They allow for spatial variations in rock properties and thermo-dynamic conditions. The principal advantage of the distributed-parameter models is that they have all the mathematics built into a computer code and allow the user to decide on how detailed (e.g., number of grid blocks), the simulation should be and what physical processes should be considered. Disadvantages of the distributed-parameter models are the need for a computer and an experienced modeler.

Choice of method

Reservoir assessment is a continuous process from the time a geothermal field is discovered to the time its development is completed. This process may extend over thirty years, so one would expect that all of the different reservoir assessment methods would be used. However, the various methods are most applicable at different stages of the project.

In the exploration stage, geological and geophysical surveys and geochemical sampling of surface springs can give indications of the areal extent and possible downhole temperature of the resource. At this stage no wells have been drilled, permeability values are not yet available and the only possible assessment method is the volumetric (stored heat) method. This method involves

estimating the total stored heat in the reservoir and then applying a recovery factor to estimate the recoverable energy. Although at this stage the available data is scarce, the approximate resource evaluation using the volumetric method is quite useful as it will determine if further investment, e.g., drilling, is warranted at the site.

When several wells have been drilled, pressure transient data should be available and analysis of the data should give estimates of the reservoir transmissivity (permeability-thickness product). At this stage, the volumetric approach should be abandoned since it does not consider permeability values, and a simple lumpedparameter model should be constructed. This model should not necessarily be developed in the same manner as earlier lumped-parameter models. We believe that if computing facilities are available, it will be much less time consuming and less costly to use an existing distributed-parameter code to perform the calculations, rather than to develop a new semi-analytic model. Our experience is that lumped-parameter models can be developed using an existing numerical simulator in a week or less, whereas a conventional semi-analytical lumped-parameter model tailored to the particular characteristics of a given field may require 6 months to a year (Grant et al., 1982). The difference is simply that the available numerical simulators have all of the mathematics already in place; such a modeling effort requires only the proper approach by an experienced modeler.

Finally, when some production history is available, the only assessment tool that can incorporate the entire set of available field data is the distributed-parameter model. It is the only model that can make a realistic evaluation of all important reservoir management questions that need to be considered.

NATURAL-STATE MODELING

Thermodynamic conditions in geothermal reservoirs evolve over geologic time. The rates at which such conditions change in the natural state are generally small in comparison to the changes induced by exploitation. Therefore, for most practical purposes, undeveloped geothermal reservoirs can be considered to be in a quasi-steady state. Efforts at quantitatively modeling this natural state can provide very useful information for evaluating a geothermal resource and for planing its development.

Quantitative modeling of the natural state must be based on a preliminary conceptual model, which in turn is developed from diverse pieces of information (i.e., geological, geophysical, geochemical, and reservoir engineering data). By quantifying its various aspects a conceptual model can be tested and refined. A successful natural state model will match quantitatively or qualitatively a wide range of observation, and in doing so will provide insight into important reservoir parameters, such as formation permeability, boundary conditions for fluid and heat flow at depth, and thermodynamic state of fluids throughout the system. Even if an unambiguous quantification of these parameters cannot be achieved, it may be possible to obtain constraints which are useful for modeling reservoir response to exploitation.

For some of the less complex geothermal systems (i.e., fault-charged low-temperature fields) successful applications of analytical or semi-analytical methods have been made. The few examples available to date suggest that natural state modeling is an important component of a comprehensive reservoir assessment. It appears to be the only way in which a consistent set of initial and boundary conditions for exploitation models can be developed.

EXPLOITATION MODELING

Tasks of a reservoir engineer include estimation of the generating capacity of a field and of well decline rates and evaluation of alternative development plans. These tasks can best be accomplished by developing a model that makes comprehensive use of all available field data. The most important field data are the reservoir properties (permeabilities and porosities), the thermodynamic state of the system (pressure, temperature, phase saturation, and chemical concentration distributions) and the exploitation history (transient flow rate, enthalpy, chemical characteristics and reservoir pressure). If all of these data are available, it is possible to construct a model that should be able to reliably predict the future behavior of the system. However, in most cases the data set is incomplete and sensitivity studies must be conducted on the most important parameters.

When an exploitation model is to be developed, the modeling approach taken should be based upon the objectives of the study. Typically, one needs to obtain answers to one or more of the following questions:

(1) What is the generating potential of the system?
(2) What is the appropriate well spacing?
(3) How fast will the production wells decline?
(4) How will the average enthalpy and chemistry of the produced fluids change with time?
(5) How will injection affect well performance?
(6) What is the effect of injection on long term reservoir behavior?
(7) Where should injection wells be located and how should they be completed?

The various types of exploitation models have different capabilities for answering these questions. Fig. 1 shows schematically the different modeling approaches.

The lumped-parameter model consists of a single reservoir block with an adjacent recharge block. It can only be expected to give a rough estimate of the generating capacity, although several investigators have attempted to use it to match enthalpy and chemical data. The lumped-parameter model is not capable of predicting long-term changes in enthalpies and chemical

concentrations because the long-term enthalpies and chemical concentrations will be those flowing from the recharge block into the reservoir block. The lumped-wellfield model, in which the entire wellfield is represented by a single or a few grid blocks, may give better estimates of the generating capacity. In addition it has the capability of predicting the long-term characteristics (enthalpy and chemical composition) of the produced fluids. The well-by-well model has the capability of addressing all the questions listed above, but for most complex geothermal systems it will have to be fully three-dimensional. The development of such models initially requires substantial manpower and computation expense to calibrate the model against all available well data.

Lumped-wellfield models

Lumped-wellfield models can be used to estimate the generating capacity of a system. Most of the models developed for geothermal fields are two-dimensional areal models, but some are vertical cross sections or two-dimensional r-z models.

If a two-dimensional lumped-wellfield model of a geothermal field is to be developed, one must carefully determine which type of model is most appropriate (i.e., areal, vertical cross section, or r-z model). The data that will most influence this decision are the hydrogeologic model of the field, the temperature-, pressure-, and chemical-concentration distributions in the natural state, and inferred patterns of natural flow. If the geothermal anomaly has an approximate circular geometry, the r-z model is much preferred over the others. It allows rather good vertical definition of the resource at a modest computing cost (a good example is the modeling of the Heber field; Lippmann & Bodvarsson, 1985). If field data indicate that recharge may be preferentially from some direction, a two dimensional areal model is usually the most appropriate. It has the disadvantage of poor vertical resolution (one layer; gravity neglected) that can lead to some errors (Faust & Mercer, 1979). However, it has the capability of modeling lateral permeability barriers and multiple upflow zones.

In general, the least attractive of the two-dimensional lumped-wellfield models is the vertical cross section model because of its limited recharge capability. Such a model may be appropriate for natural state studies, especially where pressure gradients are fairly uniform in one direction and the cross flow is therefore negligible. This is the case with many geothermal fields. However, during exploitation, a three-dimensional pressure anomaly is created and recharge into the wellfield generally occurs from all directions. The two-sided recharge assumption built into the vertical cross section model is inappropriate for most geothermal systems (Lippmann & Bodvarsson, 1983). An exception is a system with very strong vertical recharge (e.g., from depth).

Three-dimensional lumped-wellfield models with of course give the most detailed results of all lumped-wellfield models. As an example, let us consider the model of the Baca geothermal field, New Mexico, developed by Faust et al. (1984). Fig. 2 shows an areal view of the grid used. The primary purpose of the modeling study was to assess the impact of geothermal

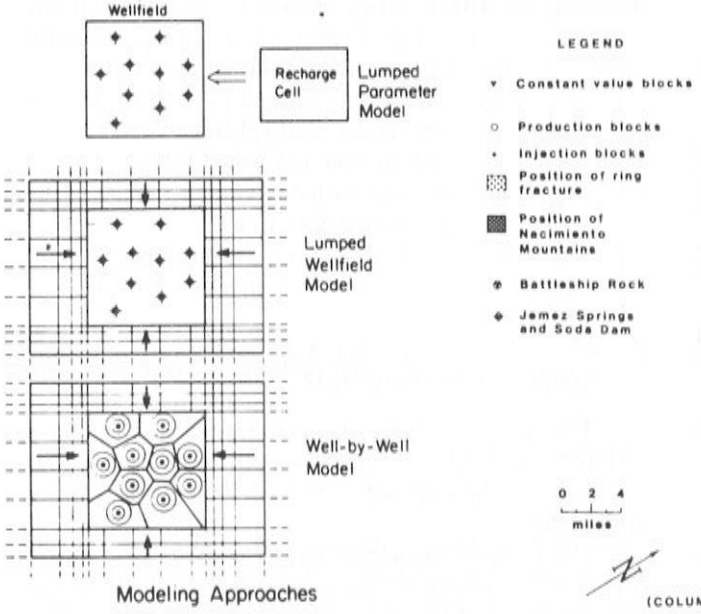

Figure 1 — Schematic representation of the different modeling approaches.

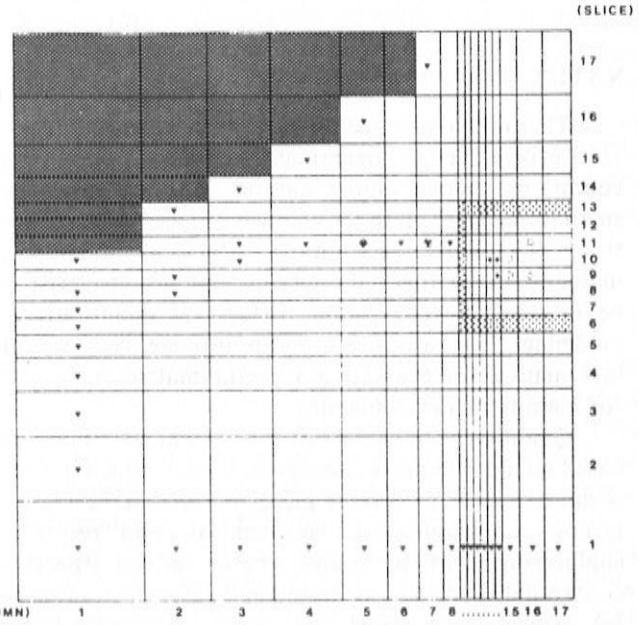

Figure 2 — Areal view of the finite difference grid used in the lumped-wellfield model of the Baca field, New Mexico (after Faust et al., 1984).

power production within the Valles Caldera on a shallow groundwater system outside the caldera. The main geothermal reservoir and the ring fracture zone are represented rather coarsely in order to follow the fluid flow patterns at large distances from the geothermal field. The model was initially calibrated against the natural conditions observed in the field (natural state model) and then used to assess the generating capacity of the reservoir and the effects of exploitation on the shallow groundwater system.

Well-by-Well Models

In developing well-by-well models one must first obtain a history match with all relevant data. For each individual well the model is calibrated against measured flow rates and enthalpies and, if possible, variations in chemical composition (dissolved solids or noncondensible gases) of the discharge. The model should also be calibrated against the observed reservoir pressure decline. Subsequently, performance predictions for individual wells and for the entire field can be made.

As an example, an areal view of the grid used in a model of the Olkaria, Kenya, system (Bodvarsson et al., 1987) is shown in Fig. 3. Note that the nodal points of grid blocks 2 through 26 correspond to actual surface locations of Olkaria wells 2 through 26. When short-term (on the order of months) flow rate and enthalpy behavior of wells is to be matched, a grid such as the one shown in Fig. 3 is too coarse. However, a satisfactory match with the early time data can be obtained by embedding a radial mesh into the grid blocks containing the wells (Pruess et al., 1984; Bodvarsson et al., 1987). The vertical dimensions of the grid are primarily determined by the locations of well feed zones.

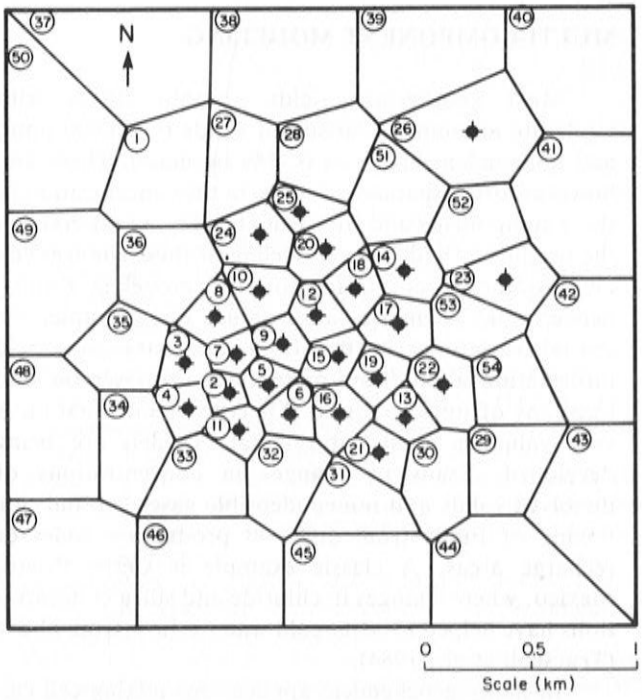

Figure 3 — The numerical grid used for the well-by-well model of the Olkaria field, Kenya (after Bodvarsson et al., 1987).

The history matching process involves numerous iterations and parameter adjustments until a reasonable agreement is obtained with the time-dependent production history. Ideally, a match with flow rates and enthalpies of all production wells, downhole pressures in observation wells, and the concentration of dissolved solids and non-condensible gases in the discharge of each well should yield a rather unique solution. In practice, however, history match models may retain a certain amount of ambiguity because available data tend to be incomplete, and because the scope of a modeling effort will be limited by cost consideration (each additional component adds one equation per grid block).

In general, one attempts to match enthalpy to within 100-200 kJ/kg (which is basically the data accuracy), and flow rate to within 1 kg/s. The history match for all will give estimates of the permeability and porosity distribution in the system. Fig. 4 shows such results for the well-by-well model of the two-phase reservoir at Krafla, Iceland (Pruess et al., 1984). In order to match the discharge history, 23 materials with different hydrological properties (permeabilities and porosities) were needed. However, the variation is not large, with transmissivity varying from 0.8 to 4.0 darcy-meters and porosity from 0.7 to 5%. The history match yields the pressure, temperature, and vapor saturation conditions throughout the system at all times.

When the history matching is completed, the model can be applied to predict future field performance for various exploitation scenarios. A rule of thumb is that reliable predictions can only be made for as many years as the history match period. However, in most cases predictions for longer periods are desired in order to obtain estimates of long-term behavior. Whereas most models can only assess the overall field capacity, the well-by-well models can actually predict future performance of all existing wells, the number of additional wells needed and proper spacing of make-up wells. For example, the Olkaria simulations show that the present well density used, 20 wells/km² (225 m spacing), is too high and that a well density of less than 11 wells/km² (300 m spacing) should be used in future drilling (Bodvarsson et al., 1987).

INJECTION MODELING

For most geothermal fields reinjection of effluents must be considered in predictions of future field behavior, because reinjection is the preferred disposal method. In modeling injection many complications arise, especially with regard to the movement of cold water fronts, and possible chemical reactions altering porosities and permeabilities of the subsurface rocks. Fig. 5 schematically illustrates a typical production-injection system for a doublet in a fractures reservoir. The fractures may short-circuit flow between injection and production wells. Another potential problem is that the separated waste water may become supersaturated with minerals.

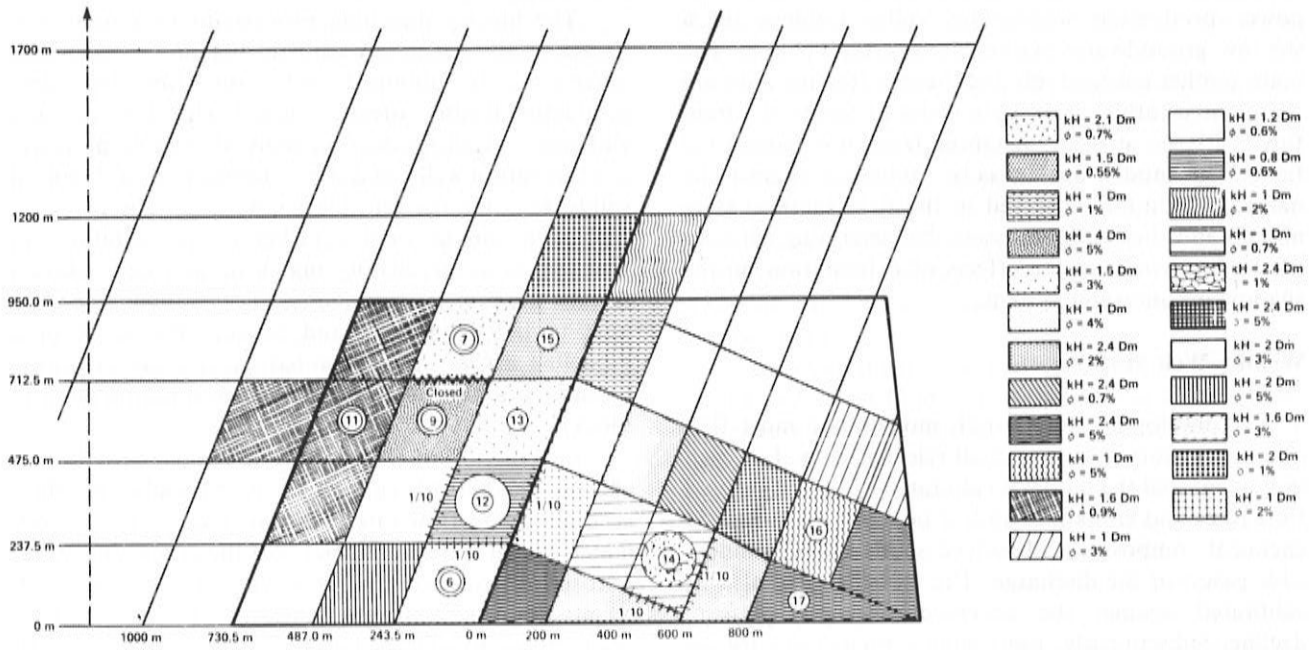

Figure 4 — Properties of different zones and flow restrictions in the lower reservoir at the Krafla field, Iceland (after Pruess et al., 1984).

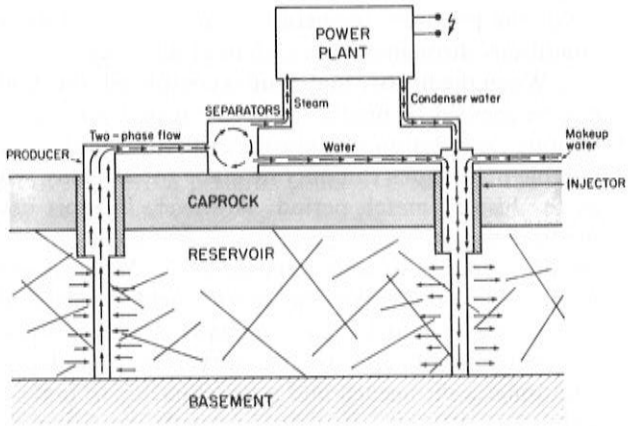

Figure 5 — Schematic figure of an injection-production doublet-well system.

The possible benefits of injection in maintaining reservoir pressure in single-phase reservoirs has been well documented in the literature. Recently, it has been predicted that injection in two-phase reservoirs can also help maintain pressures and reduce the number of make-up wells needed (Schroeder et al., 1982; Bodvarsson et al., 1985).

The modeling of injection effects on pressure transients in geothermal reservoirs is rather straightforward in comparison to modeling the advance of the cold water front away from injection wells. For longterm pressure transient or exploitation calculations porous medium models may often give good approximations for fractured systems; however, the modeling of cold water fronts necessitates the use of fracture models. One potential problem with cold water injection is premature breakthrough at the producing wells, which would reduce the enthalpy and temperature of the produced fluids. In order to predict the cold water advance it is necessary to know the fracture patterns in the system (Pruess & Bodvarsson, 1984). Such information is not available for most geothermal systems. However, it may be possible to predict the cold water advance using tracer tests (Pruess & Bodvarsson, 1984; Walkup & Horne, 1985) or geophysical methods (Pruess et al., 1983).

MULTI-COMPONENT MODELING

Most geothermal fields contain fluids with moderate amounts of dissolved solids (< 20,000 ppm) and noncondensible gases (< 1% by mass). There are, however, often spatial variations in the concentration of these components and transient changes are observed in the produced fluids. The modeling of these changes can give additional constraints on the modeling results, hence, make them less ambiguous. For example, the spatial variations in the fluid chemistry can yield information about flow patterns in the reservoir and locations of upflow zones; this type of information is very valuable when natural state models are being developed. Transient changes in concentrations of dissolved solids and noncondensible gases can indicate mixing of fluids from different production zones or recharge areas. A classic example is Cerro Prieto, Mexico, where changes in chloride and silica concentrations have helped identify cold water inflow from above (Truesdell et al., 1984).

In many geochemical applications mixing cell calculations are performed to study the origin of the fluids and determine fluid flow patterns (Henley et al. 1985).

An example of the use of multi-component modeling is given by Lai et al. (1985). They considered data from the Ellidaar geothermal field in Iceland that show pressure, temperature, and silica decline in the reservoir due to exploitation. Using a simple lumped-wellfield model they were able to obtain estimates of the reservoir volume and effective porosity in addition to permeability values for the reservoir and the caprock. Another example is the modeling of radon transport in geothermal systems, discussed by Semprini & Kruger (1983). They analyzed the transient changes in the radon content in the discharge during drawdown tests and found a reasonable agreement with data observed at The Geysers and Cerro Prieto geothermal fields.

As mentioned earlier there are fields where multi-component modeling is essential because of high concentrations of dissolved solids (e.g., Salton Sea, California) or noncondensible gases (e.g., Broadlands and Naughwa, New Zealand). These constituents can not only alter the fluid properties (e.g., densities, enthalpies and visconsities) but also the thermodynamic relationships of two-phase mixtures. Noncondensible gases have been modeled, among others, by Atkinson et al. (1987), Zyvoloski & O'Sullivan (1980), Pritchett et al. (1981), O'Sullivan et al. (1985).

SUMMARY

Geothermal systems are complex and dynamics systems where various hydrological, thermal, chemical and mechanical processes occur. They possess individual characteristics so that no universal modeling strategy is applicable to all of them. However, modeling studies of geothermal reservoirs are essential in order to optimize the development of a resource.

When a geothermal system is to be evaluated, all relevant field data must be integrated into a conceptual model. The model should be verified by natural state modeling and the natural mass and heat transfer in the system quantified. In determining the proper approach for exploitation studies, e.g., lumped-parameter, lumped-wellfield or well-by-well model, one must carefully determine what questions are to be addressed. The complexity of the modeling effort should also be consistent with the quantity and quality of the available data. It is generally advisable to start with the simplest possible model that can explain the field data, and if the data allows, attempt to include spatial or temporal variations of selected chemical components. The addition of even one component can give added insight into the behavior of the system, and make the modeling results less ambiguous.

At present it appears that there are sophisticated methods available for modeling geothermal systems (Bodvarsson et al., 1986); however, high quality field data are needed. Long term production histories are being obtained at various geothermal fields worldwide. Geothermal simulators should be applied to these data in order to validate them and to document their usefulness in geothermal reservoir evaluation.

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