GEOTHERMAL RESERVOIR MODELING NEEDS FROM EXPLORATION TO UTILIZATION

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INTRODUCTION

The decision to proceed with full scale development of a geothermal field will be determined primarily by the confidence that can be placed in its satisfactory long-term productivity. A continuously updated numerical simulation of the geothermal system, based on physical principles and the indirect measurements of the characteristics of the reservoir available at the various stages of development of the resource, can be a key tool in making realistic long-term forecasts. For example, during the exploration and development stage, the natural preproduction flow of the fluid within the system will be dominant, except in the immediate vicinity of any exploratory wells. During the full-scale extraction and utilization stage, however, the effect of the natural flow system will likely be swamped by the flow imposed by the production and injection wells.

PREPRODUCTION RESERVOIR SYSTEMS

For geothermal reservoirs it is necessary to predict both the quantity of fluid that can be produced and its temperature, in order to estimate the total usable energy of the resource. In the case of hydrothermal geothermal systems, the resource is a flowing convective fluid heated at depth and rising towards the surface as a result of the reduced density. The system is not only non-isothermal but also a dynamic system, as a consequence of buoyant flow. The three-dimensional temperature field is profoundly affected by the heterogeneity of the reservoir porosity and permeability (e.g., rock types, geologic structure, faults, etc.).

For realistic simulation of hydrothermal reservoir performance, it is necessary first to establish the preproduction temperature and flow fields. Figure 1 depicts a vertical section of a region within the Salton Sea Geothermal Field (SSGF) that is being modeled at Systems, Science and Software (S^3). By using a reservoir simulator to synthesize the available information, a model has evolved that contains cold groundwater influx upstream into the dipping and thickening upper reservoir and a hot fluid convective source from the hotter lower reservoir. The preproduction velocity field in the upper reservoir calculated from the model is shown in Figure 2. Since the model is only as good as the input physical data, and only very limited information is available, it will need modifying as more information is generated.

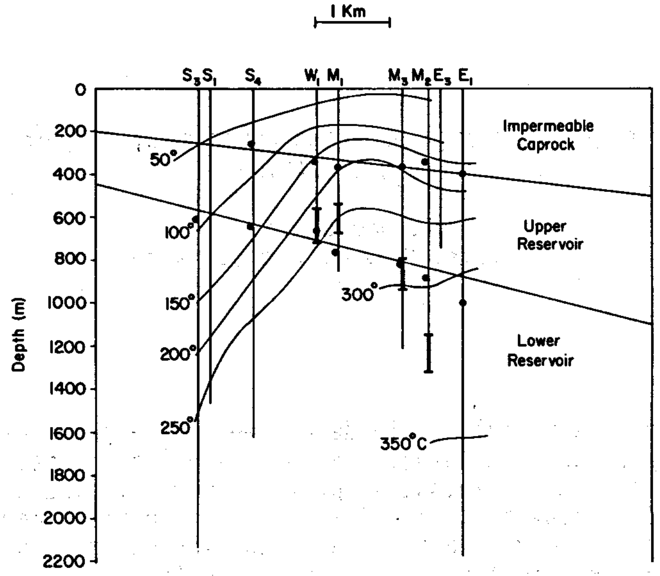

Figure 1. Vertical Section of Reservoir Model and Projected Data from Wells in Portion of SSGF Chosen for Study

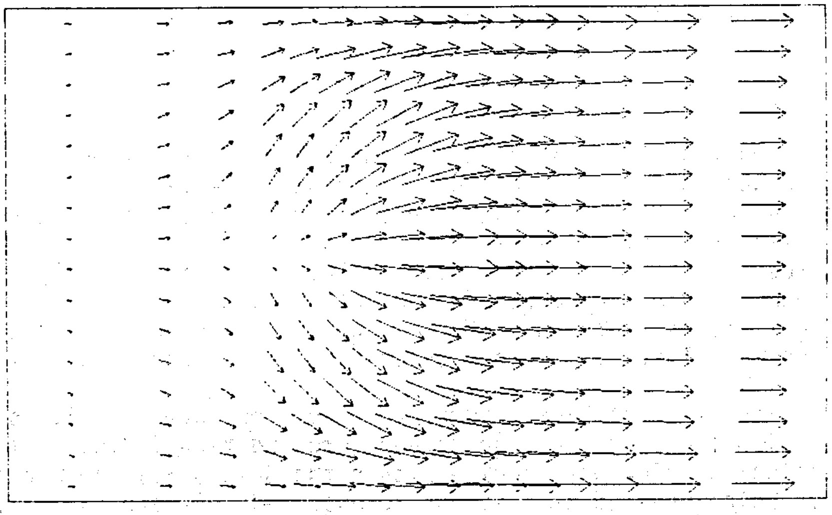

Figure 2. Preproduction Velocity Field in Upper Reservoir of a Portion of SSGF Studied

Geopressured geothermal aquifers in the U.S. Gulf Coast area are isolated by impermeable shale above and below and segmented and isolated laterally by growth faults. The preproduction temperature and pressure head are nearly uniform, and the system is essentially static. Although the initial conditions for reservoir performance calculations are simpler than for a dynamic hydrothermal system, simulation of the reservoir response to extraction is not at all simple. Basically, there are four driving mechanisms which tend to expel fluid from the aquifer (water compressibility, pore collapse, evolution of methane gas, and clay dehydration or "shale dewatering") and two which tend to impede fluid flow (decrease in permeability, which accompanies pore collapse, and relative permeability effect due to evolution of free natural gas).

RESERVOIR RESPONSE SIMULATION

There has been excellent progress at S^3 and elsewhere (1) in developing computer programs, such as QUAGMR, which solve the equations of heat flow and unsteady Darcian fluid flow in geothermal reservoir systems described in one, two, or three spatial dimensions. The work at S^3 appears to represent the current state of the art and has been summarized in Figure 3.

QUAGMR (1975 - 1977)

- Unsteady fluid and heat flow
- Compaction effects on porosity, permeability
- 1-D, 2-D, or 3-D
- Arbitrary stratigraphy, grid shape, boundary conditions
- Multiphase (water and steam) systems

MUSHRM (1976 - Present)

- All of the above
- Also treats multispecies pore fluid mixtures:
    - H_2O (Water-Steam - equivalent to QUAGMR)
    - H_2O/Methane (Water-Dissolved Gas-Free Gas)
    - H_2O/NaCl (Water-Steam-Dissolved Salt-Precipitated Salt)

Figure 3. Summary of Capabilities of Two Reservoir Simulators Developed at S^3 Over Past Five Years. QUAGMR has been superseded by More General MUSHRM Simulator

The numerical method used in QUAGMR properly treats the effects of phase change (liquid $\rightleftarrows$ vapor) within the pores of the reservoir rock (2). Each computational zone in the finite difference mesh may contain a different rock type characterized by density, porosity, directional absolute permeabilities, relative permeability functions, heat capacity, thermal conductivity, porosity-pore pressure relation, and permeability-porosity relation. Provision is made for all practical boundary conditions. QUAGMR was used in a history match study of the Wairakei field in New Zealand (3).

The MUSHRM simulator is a generalization of QUAGMR to include species mass balance and constitutive relations for water/species mixtures. One version includes a methane mass balance relation and constitutive relations for water/methane mixtures. It includes treatment of all the important drive mechanisms in geopressured geothermal aquifers and has been employed to study such systems (4). A second version includes a sodium-chloride mass balance relation and constitutive relations for single- and two-phase water/sodium-chloride mixtures. It also includes provisions for salt precipitation within pores and is being applied to a portion of the SSGF. T_{max}, in Figure 4, corresponds to the hottest part of the vertical section in Figure 1. The corresponding pressures and flash temperatures are shown for water ($s = 0$) and two brines ($s = 0.20, 0.25$). Since the presence of a vapor region within a system strongly affects reservoir behavior, it is clear that the salinity of the brine is an important input to a model, and an adequate constitutive package is essential for realistic modeling.

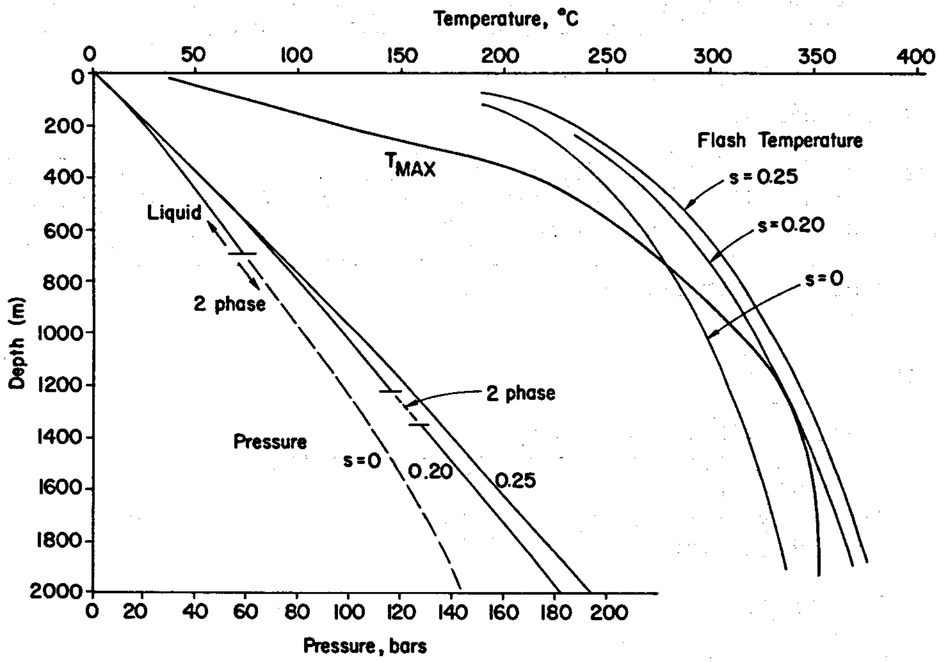

Figure 4. Pressure-Depth and Flash Temperature-Depth Curves Calculated assuming T_{max} Versus Depth Profile and Using S^3 Brine Equation of State for Fluids of Indicated Salinities

WELLBORE/RESERVOIR SIMULATORS

Reservoir simulators provide the average pressure, temperature, and so forth, within each computational zone of the finite difference mesh. To make meaningful predictions of the production at the wellhead of a wellbore perforated within the grid block, it is necessary to relate both the simulator grid block pressure to the sandface pressure and the sandface conditions to the wellhead conditions at the surface. Analytic techniques for calculating the sandface conditions are straightforward for single-phase flow. Since the temperature drop is small and the pressure drop large, however, the actual flow within the grid block may be two-phase even though the grid block conditions infer single-phase flow. The procedures that are commonly used for calculating the sandface conditions for two-phase gas/oil mixtures do not adequately treat this anomaly. At S^3 we use a technique involving subzoning of grid zones containing wells and solving the appropriate relations governing two-phase flow. The procedure accounts for the anomalous case as well as the case in which two-phase flow occurs throughout the grid block.

Several empirical correlations to calculate holdup and frictional pressure drop in vertical two-phase flow have been developed, primarily for gas/oil mixtures. The correlations are based on insufficient data and lead to serious errors when extrapolated to other flow conditions (5); data on flowing geothermal wells is needed. At S^3 we have written a program for wellbore flow of water-steam and water-methane gas mixtures. It is being incorporated into the MUSHRM simulator, along with the procedure for determining the sandface conditions from grid block values to treat coupled reservoir-wellbore systems. Application of such coupled reservoir-wellbore simulators can help interpret short-term pressure tests conducted in exploratory wells.

SUBSURFACE/SURFACE SYSTEMS

Once a hydrothermal field is under significant production, the natural groundwater and convective fluid transport will decline in importance relative to the flow associated with production/injection wells, and the temperature and pressure of the produced fluid will decrease. For example, the production of 500 kg/sec of fluid (corresponding to ~ 50 MWe) from the SSGF upper reservoir would change the preproduction velocity field shown in Figure 2 to that shown in Figure 5. Assessment of the suitability of a site includes estimating the long-term producibility of the reservoirs and the conceptual design of a suitable power plant matched to the changing characteristics of the "fuel" supplied by the reservoir over the design life of the plant.

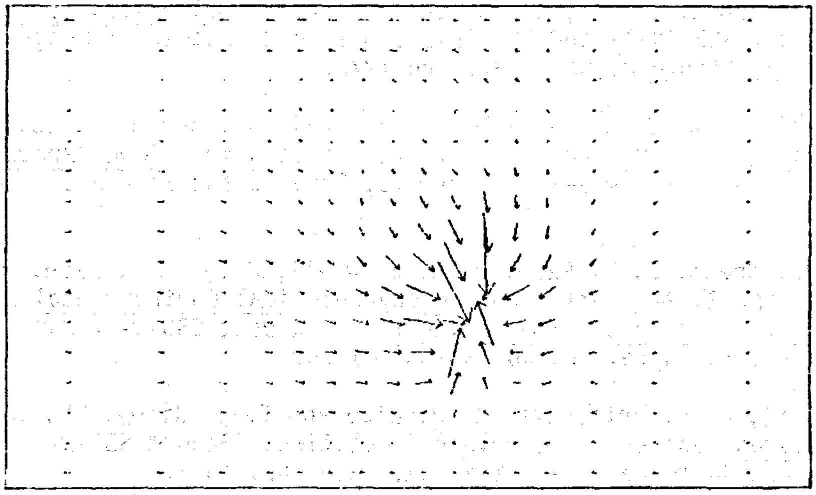

Figure 5. Velocity Field in Upper Reservoir of Portion of SSGF Studied. Simulation Depicted after 6 Months Production of Fluid at the Rate of 500 kg/sec.

Once a site is selected for a demonstration plant and a final design is initiated, it is essential that a more detailed analysis be made of the continuous interaction between the quality of the fuel supplied and the plant design. For example, the detailed power plant design, capital cost estimates, and engineering construction schedule over the design life will be sensitive to changes in the temperature and pressure of the geothermal fluid supplied to the plant. The quality of the geothermal fluid delivered and the quantity required could be forecast by simultaneously considering the reservoir flow, production wellbore flow, and the flow in the surface gathering lines. The treatment of the integrated system requires coupling of computational procedures for analyzing the individual segments.

CONCLUDING REMARKS

It is the author's opinion that numerical simulators for studying reservoir response to fluid production/injection are in fairly good shape. An immediate fruitful area of research is the development of preproduction models for specific geothermal resources. In the exploration and assessment stage of development, uncertainties in the model could be used to suggest sites for exploration wells. Planning of well tests for reservoir verification could be based on resolving major uncertainties in the evolving model. Response of the reservoir under large scale exploitation could be predicted with more credibility if the preproduction situation were matched prior to forecasting its behavior under various production/injection strategies. Such studies may form the basis for operators of adjacent leases to unitize the exploitation of a reservoir system.

Application of coupled reservoir/wellbore simulators to interpret well test data for specific sites is clearly needed. In the near future, the author believes the requirement for managing the fluid production/injection strategy to the needs of a specific power plant will lead to the development of integrated models coupling the subsurface/surface flow system to the power plant processing of the fluid.

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