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# GEYSERS INJECTION MODELING

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# GEYSERS INJECTION MODELING

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## ABSTRACT

Our research is concerned with mathematical modeling techniques for engineering design and optimization of water injection in vapor-dominated systems. The emphasis in the project has been on the understanding of physical processes and mechanisms during injection, applications to field problems, and on transfer of numerical simulation capabilities to the geothermal community.

This overview summarizes recent work on modeling injection interference in the Southeast Geysers, and on improving the description of two-phase flow processes in heterogeneous media.

## INTRODUCTION

Vapor-dominated geothermal reservoirs are naturally water-short systems. Fluid reserves tend to get depleted during exploitation much more quickly than heat reserves. Injection of water is the primary means by which dwindling fluid reserves can be replenished, and field life and energy recovery be enhanced. Effects of water injection are not always beneficial, however, because thermal degradation or water breakthrough may occur at neighboring production wells.

The design and optimization of injection operations require reliable numerical modeling techniques. This is not an easy proposition. Water injection into vapor-dominated zones is a very complex process of immiscible displacement, which is further complicated by gravitational instability of water over steam, and by strong coupling between fluid flow and heat transfer with phase change (boiling and condensation). Viscous instabilities at the water-vapor interface may also come into play (Fitzgerald et al., 1994).

We have developed a general-purpose geothermal reservoir simulation tool, TOUGH2 (Pruess, 1991a). This simulator is capable of modeling most of the reservoir processes during injection, including appearance and disappearance of liquid and vapor phases, boiling and condensation, multiphase flow due to pressure, gravity, and capillary forces, and vapor adsorption with vapor pressure lowering. It is applicable to flow systems of arbitrary geometry from one to three dimensions, and has special provisions for flow in fractured-porous media. The code is available to the public through the U.S. Department of Energy's software distribution center.† TOUGH2 has recently been enhanced with a package of pre-conditioned conjugate gradient solvers, making possible the simulation of problems with 10,000 grid blocks or more on PCs (Antunez et al., 1994).

The present report summarizes recent attempts to model injection effects at The Geysers, and to improve modeling capabilities for heterogeneous media. Accompanying laboratory efforts directed at fracture relative permeability measurements have been reported elsewhere (Persoff et al., 1991; Persoff and Pruess, 1994).

## INJECTION AT THE GEYSERS

Since the mid-eighties, reservoir pressures and well production rates at The Geysers have entered a period of accelerated decline (Goyal and Box, 1990; Enedy, 1992). Steam shortfalls have curtailed power production and have emphasized the need to view injection not just as a means for condensate disposal, but as a reservoir management tool for replenishing dwindling fluid reserves and enhancing energy recovery.

† *Energy Science and Technology Software Center, P.O. Box 1020, Oak Ridge, TN 37831; phone (615) 576-2606.*

In an effort to replace mass withdrawals at The Geysers, Unocal has injected condensate since 1969 (Barker et al., 1992). Beginning in 1980 this was augmented with fresh water from Big Sulphur Creek. Water injection and reinjection is now standard operating practice throughout The Geysers field. Through careful decline curve analysis, Goyal and Box (1992) and Enedy et al. (1991) have been able to quantify in detail the substantial production gains from injection. However, in some cases detrimental effects from injection have been reported, such as breakthrough of water at production wells (Barker et al., 1992).

Recent injection experiments performed by Northern California Power Agency (NCPA) in the Southeast Geysers have shown dramatic patterns of interference with production (Enedy et al., 1991; Pruess and Enedy, 1993). During 1990 water was injected into a well called Q-2 for periods of from one to several weeks at rates of 200-600 gpm (approximately 12-36 kg/s). A nearby production well, Q-6, responded to injection with rapid strong rate declines. When injection was stopped production not only recovered but over-recovered. As shown in Fig. 1,† the interference pattern could be repeated over many injection cycles, and (over-)recovery of production was stronger for longer periods of injection shut-in.

The NCPA test has yielded unique field data on injection-production interference. Replicating these effects would be a severe test on the capabilities of numerical simulation models. We have developed a model that attempts to capture in detail the reservoir conditions and processes deemed responsible for the peculiar observed behavior (Pruess and Enedy, 1993). The strength and rapidity of interference between Q-2 and Q-6 suggest that both wells intersect the same fractures or fracture zones. Accordingly, our simulation model contains a vertical fracture and a large background reservoir (Fig. 2). Numerical simulation of the process was made with LBL's general-purpose TOUGH2 reservoir simulator. Heat transfer from the wall rock to the fracture was included, as were effects of finite wall rock permeability. An "effective continuum" treatment was employed for the fractured-porous background reservoir. Full details are given in (Pruess and Enedy, 1993).

Typical results are shown in Fig. 3. Prior to start of injection the production well is placed on deliverability. Production is simulated for a five-year period to obtain reasonably stabilized rates. When subsequently injection is started, production rate is seen to decline through a combination of temperature, pressure and relative permeability effects. When injection is terminated production rates not only recover but over-recover. This behavior agrees with the field observations, although no attempt was made to match them in quantitative detail.

The main results from this study can be summarized as follows (for a more detailed discussion see Pruess and Enedy, 1993). (i) Current numerical modeling techniques are capable of simulating the highly non-linear fluid flow and heat transfer processes during injection in considerable detail, even including the complications of flow in highly permeable fractures. (ii) The most significant reservoir processes during injection include gravity-driven downward migration of injected water, local heat exchange between the injection plume and reservoir rock, capillary imbibition of injected water into matrix rock, vapor condensation in cooler portions of the plume, and boiling in the hotter portions. (iii) Injection is subject to heat transfer limitations. Cooler portions of injection plumes consume large amounts of reservoir steam, while hotter portions contribute additional steam. (iv) From the standpoint of reservoir management, injection should not be concentrated in a few wells operating at large rates. Better pressure support is achieved by distributing injection among many wells with modest rates, well below their capacity for accepting fluids.

## PHASE DISPERSION

Numerical simulation of injection is subject to grid orientation effects, i.e., simulation results depend not only on grid spacing but also on the orientation of the grid relative to the vertical (Pruess, 1991b). This is demonstrated by modeling injection into the system shown in Fig. 4, which represents a vertical section through a depleted vapor zone. Using "parallel" and "diagonal" grids (Fig. 5) results in dramatically different predictions

† *Figures at end of paper.*

for injection plumes (Fig. 6). More consistent (less grid-dependent) results are obtained when a higher order ("9-point") differencing method is used (Fig. 7). The grid orientation effect arises from an interplay between the hydrodynamic (gravitational) instability and anisotropic numerical dispersion. A more careful analysis suggests that the 9-point results are not necessarily "better;" they avoid obvious inconsistencies simply because the numerical dispersion effects are more nearly isotropic.

In order to attain a physically realistic description of the behavior of injection plumes, it is necessary to explicitly represent the physical dispersion of liquid plumes from medium heterogeneities.

Water injection in fractured vapor-dominated reservoirs is dominated by gravity effects, which tend to pull the injection plume downwards. However, "straight" downward flow is only possible when appropriate permeability is available in the vertical direction. Water flowing downward in sub-vertical fractures is likely to encounter low-permeability obstacles, such as asperity contacts between fracture walls, or fracture terminations. Water will pond atop the obstacles and be diverted sideways, until other predominantly vertical pathways are reached (Fig. 8). By accounting for this process of heterogeneity-derived dispersion, artifacts from numerical dispersion become less significant, and more realistic simulation of injection into vapor-dominated systems can be achieved.

We have developed an approach that seeks to account for heterogeneity-derived phase dispersion by a suitable extension of conventional multiphase flow theory (Pruess, 1994). Liquid and vapor fluxes are usually expressed with a multiphase version of Darcy's law, as follows.

$$\mathbf{F}_\beta = -k\frac{k_{r\beta}}{\mu_\beta}\rho_\beta\left(\nabla P_\beta - \rho_\beta \mathbf{g}\right) \qquad (1)$$

The index $\beta$ denotes liquid or vapor phase, k is the absolute permeability, $k_{r\beta}$ is relative permeability for phase $\beta$, $\mu$ is viscosity, $\rho$ is density, $P_\beta$ is pressure in phase $\beta$, and g is acceleration of gravity. We propose to model phase dispersion in analogy to Fickian diffusion by adding a dispersive flux term for liquid phase to Eq. (1), which is written as

$$\mathbf{F}_{l,\mathrm{dis}} = -\rho_l\,\phi\,\mathbf{D}_{\mathrm{dis}}\,\nabla S_l \qquad (2).$$

Here, $\phi$ is porosity, and **D** is the dispersion tensor. Dispersive flux is presumed to be proportional to the gradient of liquid saturation, $S_l$. The validity of the proposed Fickian dispersion model was examined by means of high-resolution numerical simulation experiments in heterogeneous media. TOUGH2 simulations with of the order of 10,000 grid blocks showed that the mean square size of descending liquid plumes tends to grow linearly with time, indicating that plume spreading indeed tends to be diffusive, and substantiating the flux model Eq. (2).

Subsequently the proposed flux term Eq. (2) was coded into TOUGH2, and calculations were made to explore phase dispersion effects during injection. A two-dimensional radially-symmetric problem was considered (Fig. 9). An injection well penetrates the top 500 m of a 1000 m thick reservoir. Problem parameters were chosen representative of depleted vapor zones at The Geysers. Liquid water is injected at a rate of 25 kg/s. The shape of injection plumes without and with phase dispersion is compared in Figs. 10 and 11. As expected, phase dispersion enhances the lateral and diminishes the vertical migration of injected fluid. An obvious implication is that neglect of phase-dispersive effects may underestimate the potential for water breakthrough at neighboring production wells. Reservoir pressure distributions may also be strongly affected. A more detailed discussion is given in (Pruess, 1994).

## SUMMARY AND CONCLUSIONS

The complex interplay between fluid and heat flow, and the presence of gravitational instabilities and reservoir heterogeneities make mathematical modeling of water injection into vapor-dominated systems extremely challenging. Currently available simulation techniques are capable of dealing with the complexity of "real" field problems as they arise at The Geysers. New developments attempt to better represent reservoir heterogeneities, to increase the size of problems that can be handled, and to make simulation capabilities available on "small"

computers, such as PCs (Antunez et al., 1994).

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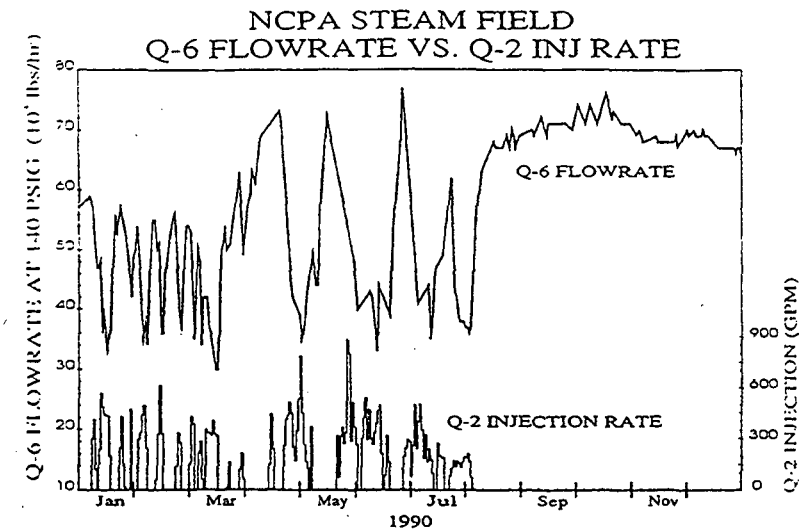


Figure 1. Injection and production data from wells Q-2 and Q-6, southeast Geysers (from Pruess and Enedy, 1993).

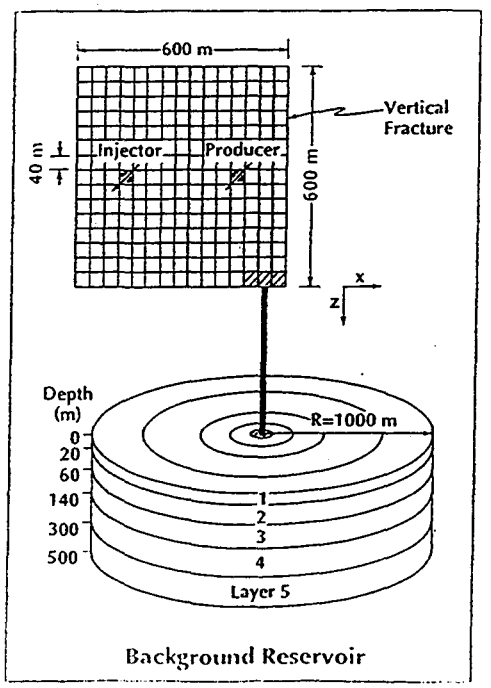


Figure 2. Schematic diagram of fractured reservoir model used in numerical simulations (Pruess and Enedy, 1993).

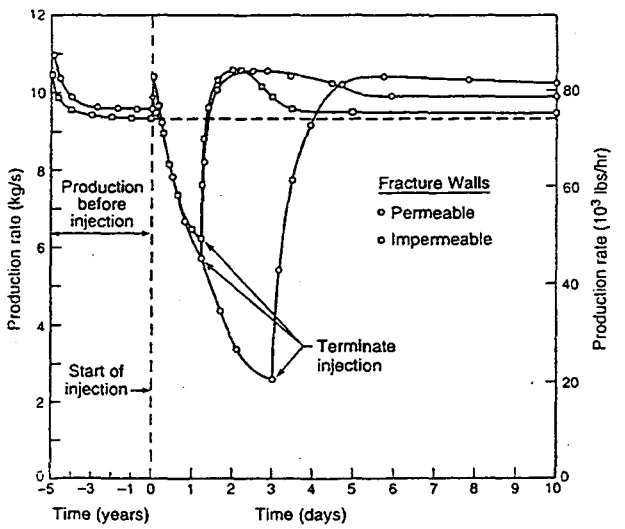


Figure 3. Simulated production before, during, and after injection (Pruess and Enedy, 1993).

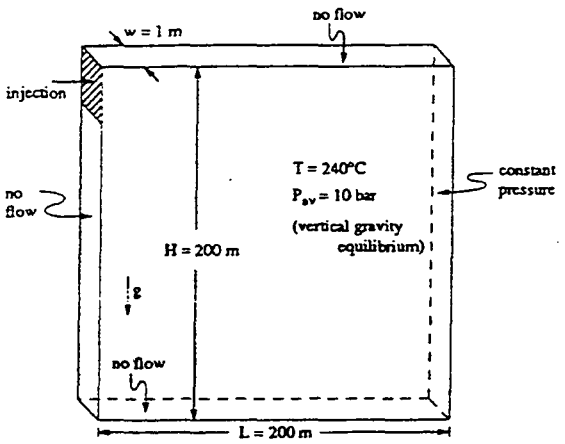


Figure 4. Vertical section model for study of grid orientation effects (from Pruess, 1991b).

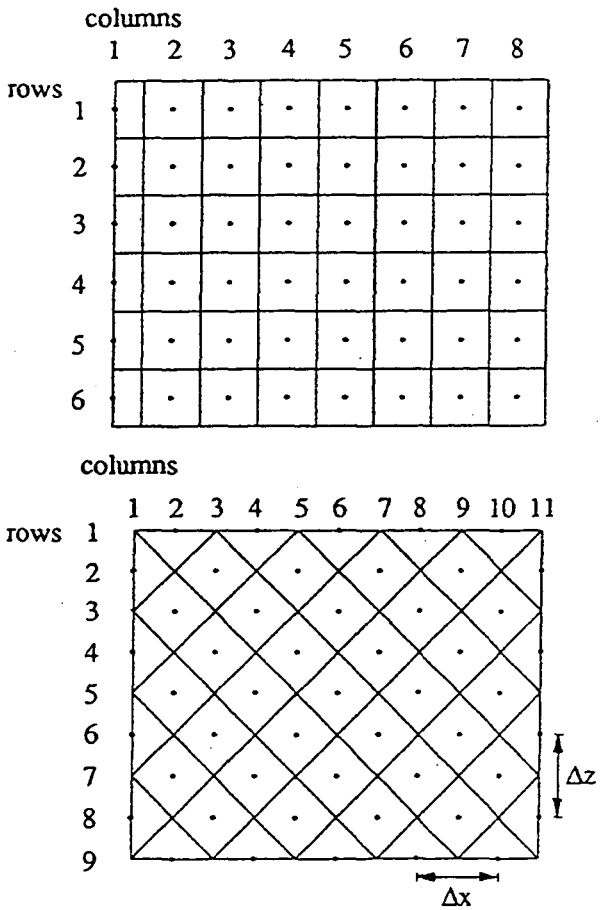


Figure 5. Schematic of "parallel" and "diagonal" grids used for modeling injection in 2-D vertical section (Pruess, 1991b).

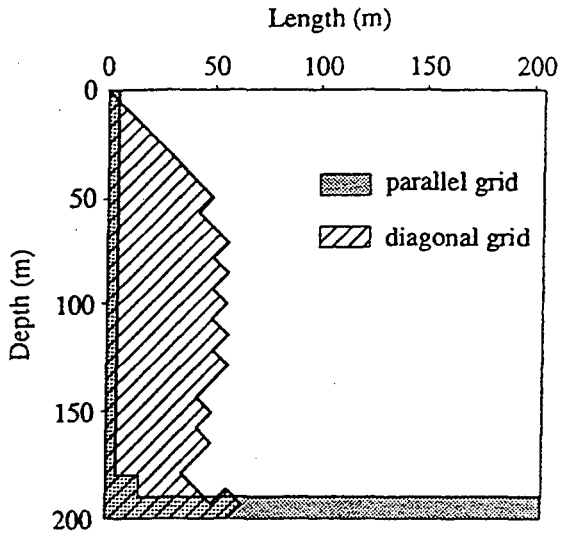


Figure 6. Simulated plumes after 717 days of injection in parallel and diagonal 5-point grids (Pruess, 1991b).

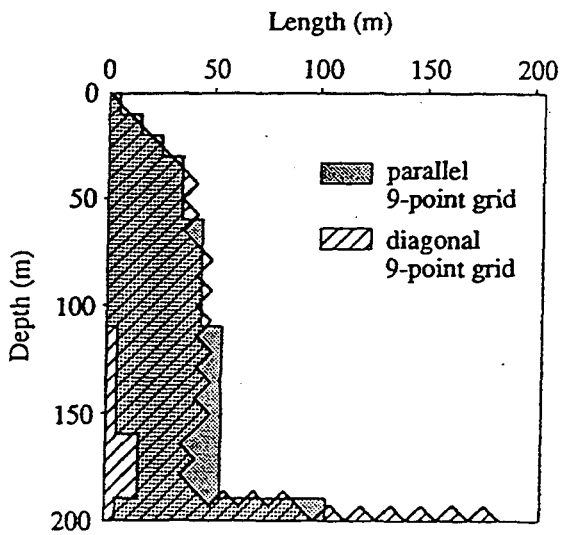


Figure 7. Simulated injection plumes after 717 days for 9-point differencing (Pruess, 1991b).

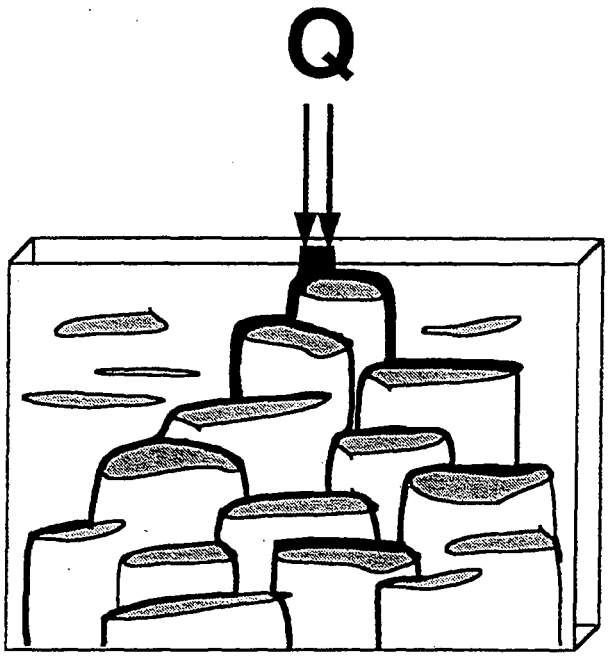


Figure 8. Schematic of liquid plume descent in a heterogeneous medium. Impermeable obstacles are shown by dark shading (from Pruess, 1994)

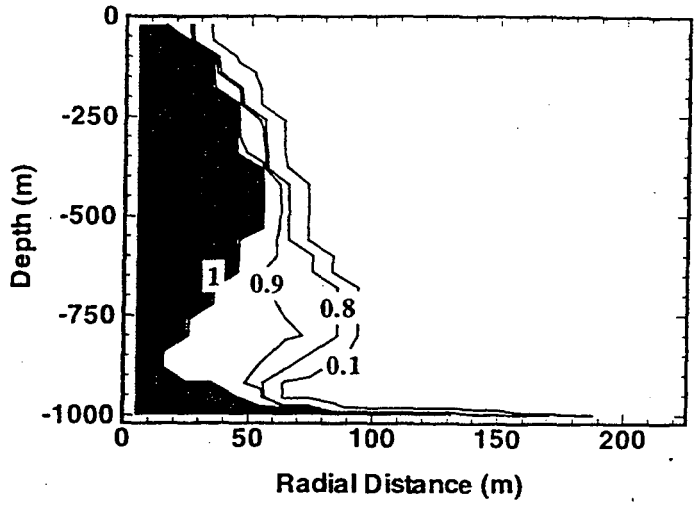


Figure 10. Injection plume (liquid saturation contours) after 692 days, no phase dispersion (Pruess, 1994).

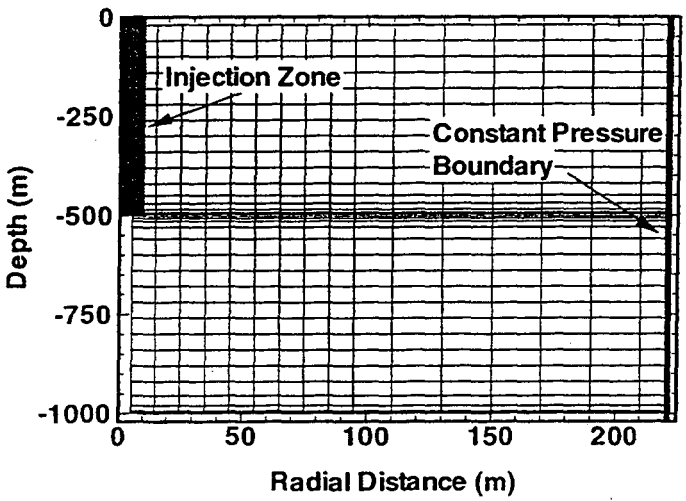


Figure 9. Gridding for 2-D R-Z injection problem (Pruess, 1994).

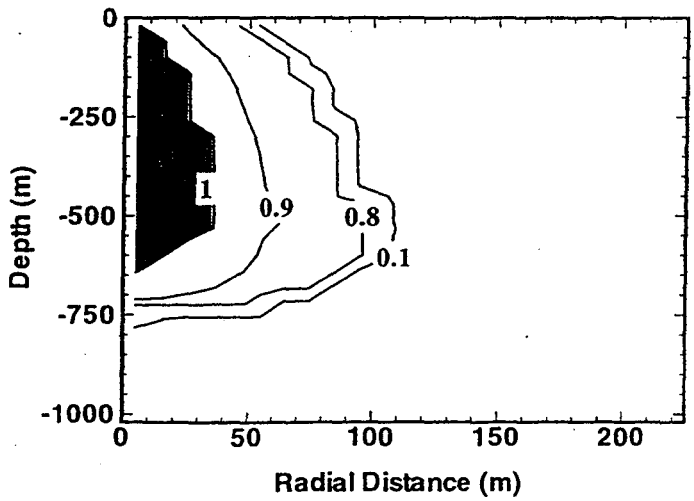


Figure 11. As Fig. 10, but transverse phase dispersivity of 10 m (Pruess, 1994).

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