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APPLICATION OF A MATRIX-FRACTURE TRANSFER PSEUDOFUNCTION IN GEOTHERMAL RESERVOIR SIMULATION

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ABSTRACT

A fine-grid, single porosity model of a matrix-fracture system was used to visualize the pressure response and mass transfer mechanisms in a vapor-dominated geothermal reservoir. The observed pressure response and saturation distributions were used to generate a pseudofunction representing the product of vapor phase relative permeability and matrix-fracture transfer shape factor for a dual-porosity model. The pseudofunction was found to be a function of vapor saturation. It was used in place of the gas relative permeability curve. With the application of the pseudofunction, the dual-porosity model produced pressure decline trends similar to those observed in the fine-grid models. The pseudofunction approach was successfully applied in the history matching of a single Geysers producing well. The TETRAD simulation code was used in this study.

INTRODUCTION

Simulation of The Geysers reservoir requires the application of a dual-porosity model. In this reservoir, the matrix contains most of the mass in-place while the fractures provide the flow channels to production wells. The conventional approach uses a matrix-fracture transfer function to calculate the mass flow rate between the matrix and the fracture (Kazemi et al., 1976). Currently, available transfer functions are based on flow in oil reservoirs where mass transfer mechanisms are different from those in geothermal reservoirs. An alternate approach for considering matrix-fracture interaction was investigated in this study. Fluid movements in geothermal reservoirs are often accompanied by phase changes as a result of vaporization and condensation of water. Our objective was to incorporate the phase changes associated with matrix-fracture transfer in geothermal reservoirs in the transfer function.

In the dual-porosity simulation model used for this study, the rate of mass transfer, q, (in barrels/day) between the matrix and the fracture is calculated using the following function (Kazemi et al., 1976, and SERVIPETROL LTD., 1991):

$$q = 0.001127 \cdot V_b \cdot \sigma \cdot k_m \cdot \frac{k_r}{\mu} \cdot \Delta\phi \qquad (1)$$

where,

V_b = bulk volume of gridblock, cu-ft
σ = shape factor, 1/sq-ft
k_r = relative permeability
μ = viscosity, cp
k_m = matrix permeability, md
$\Delta\Phi$ = potential difference between matrix and fracture, psi.

The underlying assumption in the derivation of an expression for σ in Equation (1) is that pseudosteady state exists in the matrix at all times (Warren and Root, 1963). This assumption may not be valid if the transient period is long.

This study used the TETRAD numerical simulator (SERVIPETROL LTD., 1991) to investigate the following: 1) representative models of a matrix-fracture system at a very fine scale, 2) how the fluid movement mechanisms in a geothermal reservoir will affect the matrix-fracture transfer calculations at a larger scale, and 3) a model of a segment of The Geysers containing one producer using a psuedofunction based on fine-grid simulations.

FINE-GRID MODEL APPROACH

A fine-grid model simulates mass transfer between the matrix and the fracture without the application of the dual-porosity concept. This eliminated the uncertainties associated with using

a transfer function used in Equation 1 to describe the matrix-fracture transfer. The fine grids enabled the visualization of the mechanisms by which mass is transported from the matrix to the fracture.

A linear, one-dimensional (1-D) model was selected as illustrated in Figure 1. The model had one gridblock representing the fracture, with the remaining 24 gridblocks representing the matrix. The model dimensions were 100 feet by 1 foot by 1 foot. The fracture gridblock dimension was 0.01 foot in width. The matrix gridblock width ranged from 0.01 foot to 29.405 feet and increased in width with distance from the fracture. It modeled an element of the matrix-fracture system with a matrix block length of 200 feet. Because of the symmetry of the system, only a 100 feet length was modeled. A closed outer boundary was assumed. Assuming a homogeneous system with uniform withdrawal from the fracture, the assumption of no-flow boundaries in the fine-grid model was a reasonable approximation for understanding the mechanisms of matrix-fracture fluid transfer. This simple, one-dimensional model was effective in illustrating the mechanisms of mass transfer.

Another model was constructed to investigate the effect of changing flow area along the flow path. It was a one-dimensional radial model, also shown in Figure 1. It was scaled to have an area equivalent to that of a single matrix-fracture sub-block in a dual-porosity model. The model size was 66.67 feet in radius and 2.865 feet thick. A total of 100 gridblocks were used. The gridblock sizes in the radial direction ranged from 0.9425 foot to 0.01 foot, with the outermost block representing the fracture (see Figure 1).

A single-gridblock dual-porosity model was also constructed. It required the use of a shape factor to model the matrix-fracture transfer. A 200 feet fracture spacing was used. The objective was to investigate how the results obtained with different shape factors in the dual-porosity model compared with those of the fine-grid model. Four different shape factors were studied. They ranged from $12/L^2$ to $100/L^2$ (where L is the matrix block length). A shape factor of $12/L^2$ is most commonly used in the petroleum engineering literature (Kazemi et al., 1976).

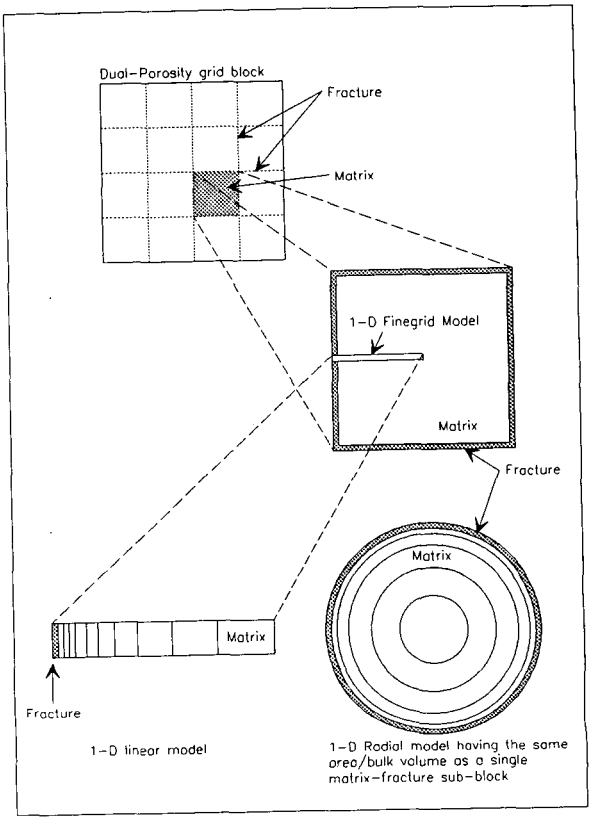

Figure 1: Schematic of Fine-grid Model Selection

Both the 1-D radial model and the single block dual-porosity model had similar fracture surface area to matrix bulk volume ratio of 0.03 sq-ft/cu-ft. This was necessary in order to compare the two models.

Matrix porosity and permeability were 0.04 and 0.01 md, respectively. A linear relative permeability versus water saturation curve was assumed. Connate water saturation was 25 percent.

A constant rate of withdrawal, equivalent to 11.5% per year of the mass in-place, was applied to all models. Mass was withdrawn from the fracture only.

RESULTS OF FINE-GRID MODELS

Figures 2 and 3 show the pressure, temperature and vapor saturation profiles of the 1-D linear model at 50 and 400 days, respectively. Pressure gradient in the matrix even at 400 days was still transient.

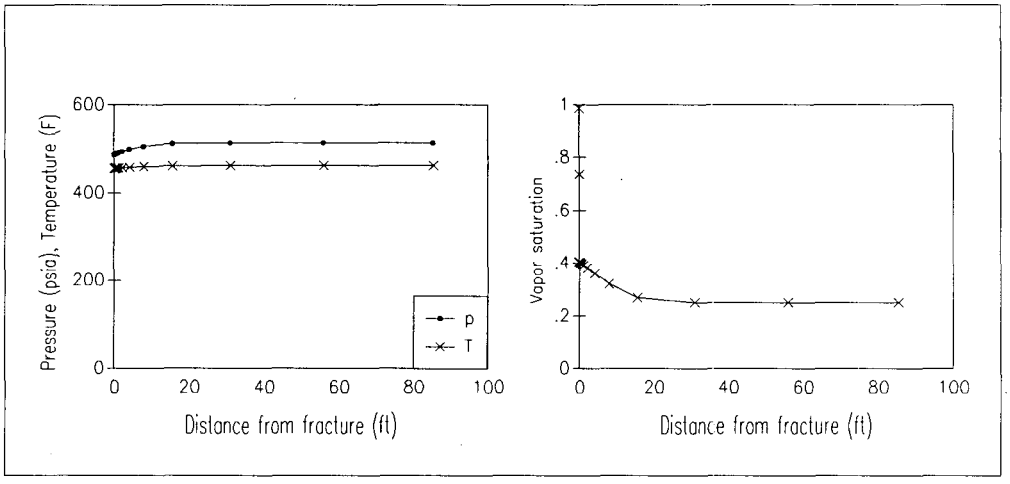

Figure 2: 1-D Linear Model - Pressure, Temperature and Saturation Profiles at 50 days

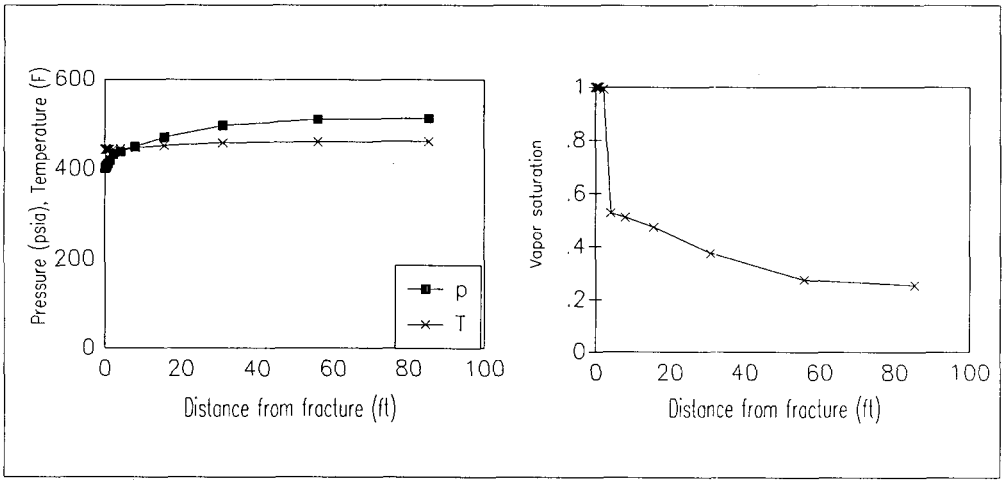

Figure 3: 1-D Linear Model - Pressure, Temperature and Saturation Profiles at 400 days

The temperature remained fairly constant throughout. The pressure profiles showed depletion with time and were dependent on the distance the pressure transient had travelled from the fracture. The vapor saturation profiles were indicative of the mass transfer mechanisms. The vapor saturation at the matrix-fracture interface were near unity or at unity at all times. The TETRAD simulator uses flat-surface boiling calculations and does not include effects of adsorption/desorption (Hsieh and Ramey, 1983). At these vapor saturations, the relative permeability to water was zero. In other words, only the vapor phase was mobile at the matrix-fracture interface. The mechanism by which mass was transferred from the matrix to the fracture was first by vaporization in the matrix. The mass was subsequently transferred through the matrix to the fracture as a single-phase vapor.

The σ in Equation (1) was back-calculated using the observed fracture and average matrix pressures, matrix temperature and vapor saturation of the 1-D radial model. Note that it no longer represents the shape factor. The computations assumed mass transfer as a single-phase vapor and that the gas viscosity was constant, since the temperature was fairly constant. The results (Figure 4) indicated that if a dual-porosity model is to be used to reproduce the fine-grid model results, this factor would have to change, especially during the early times of production.

COMPARISON OF RESULTS OF 1-D RADIAL AND DUAL-POROSITY MODELS

Figure 5 summarizes the calculated fracture pressure responses. The matrix pressures were almost identical for all

cases. The fracture pressure decline rate increased with time in the fine-grid model, while those of the dual-porosity model showed a slower decline rate after about 1200 days. The expanding vapor saturated zone in the 1-D radial model, which increased the distance mass (water) had to travel from the matrix to the fracture, probably caused the increased pressure decline. On the other hand, the 'distance' between the matrix and the fracture in a dual-porosity model was fixed. As a result, the trend of pressure decline in the dual-porosity model was strongly influenced by the relative permeabilities to gas and water.

The major difference between the two types of models was the mechanism of mass transfer from the matrix to the fracture. The fine-grid models indicated that mass was transferred from the matrix to the fracture as a single-phase vapor. On the other hand, the dual-porosity model assumed a two-phase (water and steam) mass transfer. The dual-porosity model assumed that one matrix block (or a group of matrix blocks as an entity) was connected to one fracture (or a group of fractures as an entity) in a given direction. Assuming the capillary pressure between vapor and water is negligible, the total mass transfer from the matrix to the fracture becomes:

$$q=0.001127 \cdot v_b \cdot k_m \cdot \sigma \cdot [\frac{k_{rw}}{\mu_w}+\frac{k_{rg}}{\mu_g}] \cdot \Delta\phi \qquad (2)$$

where the subscript w and g denote water and vapor phase, respectively.

Since the average water saturation of the matrix did not reduce to zero or to a value below the residual saturation, the mobility of water resulted in liquid phase mass transfer being computed. Therefore, it was not surprising that a dual-porosity model could not reproduce the results observed in the fine-grid model, regardless of the shape factor used.

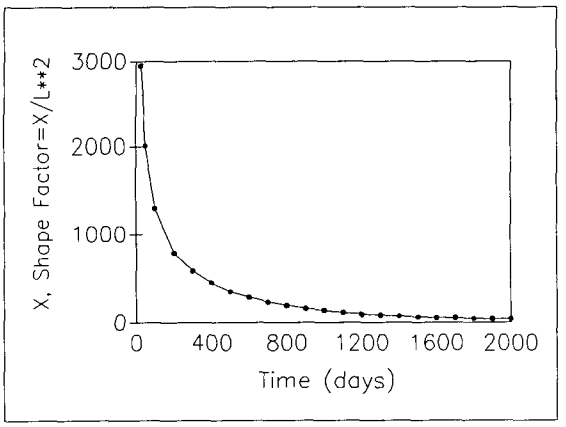

Figure 4: Calculated Shape Factor from Fine-grid 1-D Radial Model

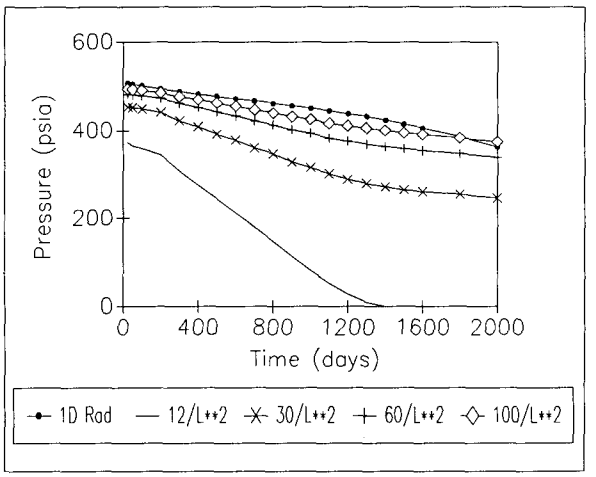

Figure 5: Calculated Fracture Pressure
Fracture surface area - matrix bulk volume ratio = 0.03 sq-ft/cu-ft

PSEUDOFUNCTION

One way of ensuring that mass transfer from the matrix is always in the form of vapor is to set the relative permeability to water in the matrix to zero and modify the relative permeability to gas. One convenient way to accomplish this is to rewrite Equation (1) as:

$$q=0.001127 \cdot V_b \cdot \sigma^* \cdot F \cdot k_m \cdot (\frac{1}{\mu}) \cdot \Delta\phi \qquad (3)$$

where,

σ^* = any appropriate fixed shape factor, 1/sq-ft

F = a dimensionless pseudofunction dependent on vapor saturation

The pseudofunction, F, accounts for the combined effects of phase changes and resistance to flow. It can be determined from the results of a fine-grid model representing the matrix-fracture system of interest. In this study the 1-D radial model described earlier was used. The calculated pseudofunction for a ratio of fracture surface area to matrix block volume of 0.03 sq-ft/cu-ft and $\sigma^*=12/L^2$ is shown in Figure 6. The results obtained by the application of the pseudofunction in

the dual-porosity model are shown in Figure 7. The results of the corresponding fine-grid 1-D radial model is also shown for comparison. A reasonable agreement between the calculated fracture pressures was obtained. Some refinements to the pseudofunction, especially at high vapor saturations, may be necessary to obtain a better match.

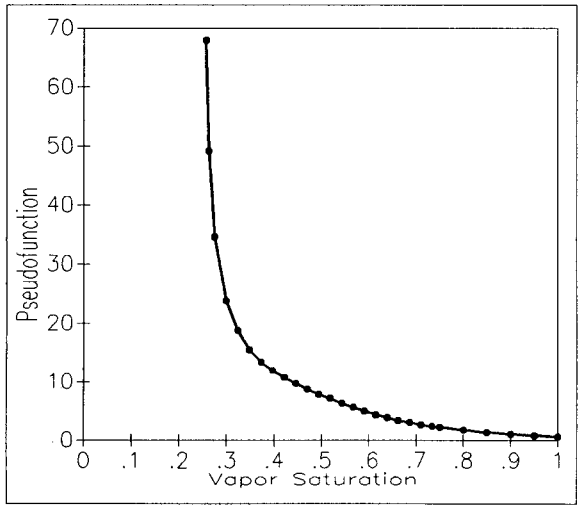

Figure 6: Pseudofunction vs Vapor Saturation

Fracture area / matrix bulk volume = 0.03 sq-ft/cu-ft
Equivalent matrix block length in dual-porosity model = 200 ft

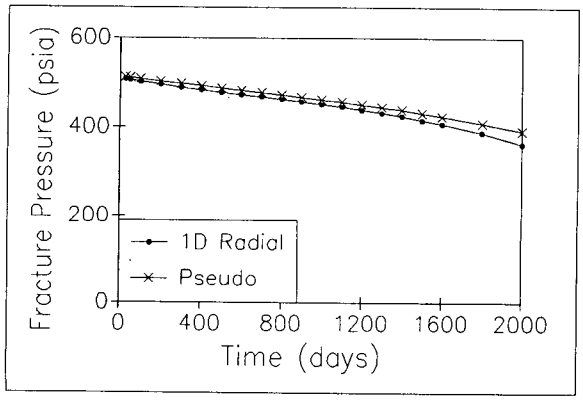

Figure 7: Results of 1-D Block Dual-Porosity Model with the Application of a Pseudofunction

1. Radius of 1-D model = 66.67 ft
2. Matrix block length in D-P model = 200 ft
3. Fracture area / matrix BV = 0.03 sq-ft/cu-ft.

MODELING A SINGLE GEYSERS WELL

McKinley-3 was selected for the purpose of applying the pseudofunction approach to model a producer at The Geysers. Sufficient data were available from McKinley-3 to enable the construction and verification of the model by history matching (Box, 1991 and California Department of Oil and Gas, 1991). McKinley-3 was drilled and completed in October 1969. Production started in early 1980. By the end of May 1991, cumulative production was 7.5 G-lb (10^9 lb).

The observed decline trend of P/Z against cumulative production is shown in Figure 8. Two distinct trends were observed: 1) an initial trend pointing to a mass in-place of 31 G-lb and 2) a current trend indicating a mass in-place of 9.1 G-lb. The apparent timing of the change in the P/Z decline trend is at a cumulative production of 4 G-lb, or the end of July 1985. The increase in pressure decline can be attributed to the increased offset steam production. The history matching process would either require flow across boundaries to allow for the withdrawal from nearby producers or a method to take into account the shrinking drainage area. The latter appeared to be the simpler approach. The approach of reinitializing a history match has been reported by Enedy (1989). In applying the Fetkovich type curve matching of McKinley-3 production history, reinitialization was made in October 1985. This compares favorably to a reinitialization of August 1985 used in this study.

A model containing 31 G-lb of mass initially in-place was constructed. A 100 year pre-exploitation run was made to allow the model to come into equilibrium. The model was subject to rate specified production from March 1980 until the end of July 1985, when the cumulative production was 4 G-lb. The gridblock parameters at the end of this run were used to reinitialize the model, but with a smaller drainage area and mass in-place. The smaller model was used for matching the current decline trend.

A dual-porosity (matrix-fracture) model with 5x5x5 gridblocks was selected. Five vertical layers of 2000 feet each were used. With a fracture permeability of 10 md, the permeability-thickness product is 100,000 md-ft which is comparable to that obtained from well tests. The well was located at the center of the topmost layer. The size of the uniform areal gridblocks was varied when adjusting the amount of mass in-place. Typical Geysers reservoir data from published literature were used (Barker et al., 1989). Appropriate modifications were made where applicable.

A pseudofunction for the field case (Figure 9) was derived by the procedure outlined earlier. The gridblock dimensions are similar to the 1-D radial model. Relative permeabilities consistent with Geysers reservoirs were used in the fine-grid model (Dykstra, 1991). The application of the pseudofunction was achieved by setting the relative permeability to water in the matrix to zero and replacing the relative permeability to gas with the pseudofunction.

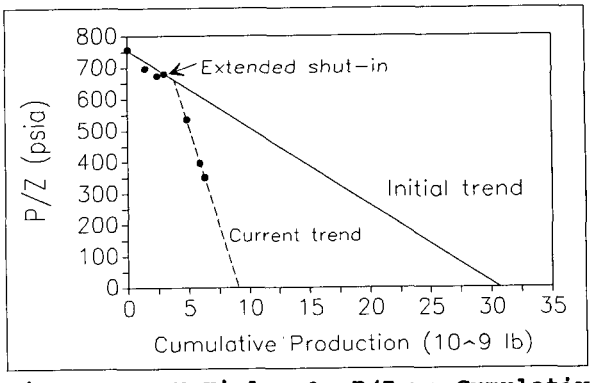

Figure 8: McKinley-3: P/Z vs Cumulative Production

RESULTS OF HISTORY MATCHING

The initial model contained 31 G-lb mass in-place. The model drainage area is approximately 2090 square feet. Rate specified production was imposed until the cumulative production became 4 G-lb. Excellent pressure matches were obtained, verifying that the mass in-place is reasonable. The results at the end of this run were used to reinitialize the model, but with a smaller mass in-place.

A reinitialized mass in-place of 11 G-lb was found to give the closest match with the observed decline trend. (Figure 10). It corresponds to a model with a drainage area of 1300 square feet. This area compares reasonably with the approximate drainage area of McKinley-3. The match was obtained without further adjustment of the input data. Results obtained using a fixed shape factor (Kazemi et al.,1976) of $12/L'$ showed a different decline trend (Figure 10).

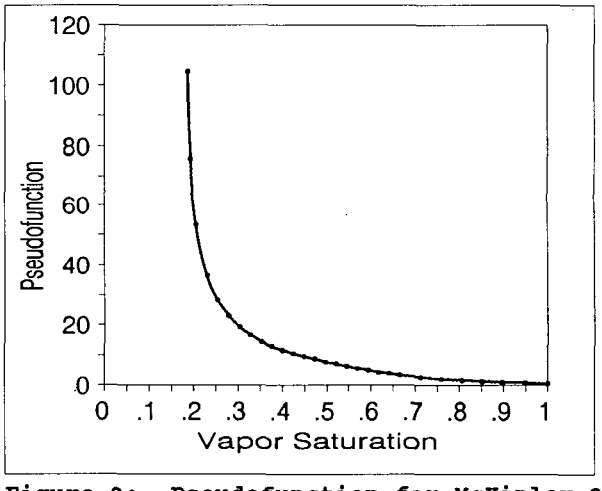

Figure 9: Pseudofunction for McKinley-3 Model

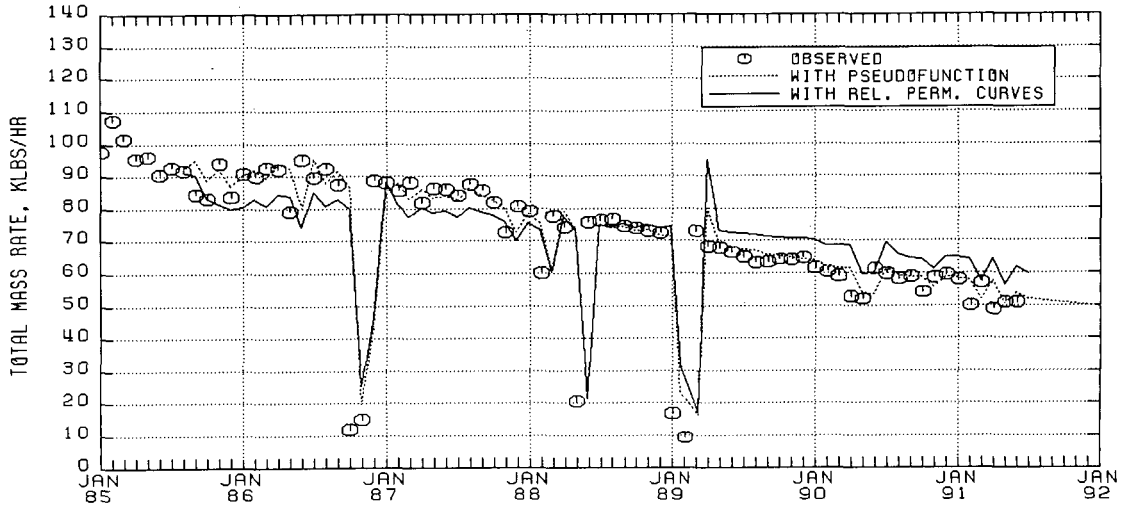

Figure 10: McKinley-3 Model History Matching

CONCLUSIONS

Based on preceeding discussions, the following may be concluded:

1. The fine-grid models indicate that mass transfer from the matrix to the fracture occurred as a single-phase vapor.

2. Mass transfer calculated using a constant shape factor in a dual-porosity model may be inconsistent with the observed transport mechanisms in a vapor-dominated geothermal reservoir.

3. A method to develop a psuedofunction which accounts for the combined effect of matrix pressure transient and single-phase mass transfer was proposed.

4. The psuedofunction has been successfully applied in the history matching of a single-well Geysers model.

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