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THE EFFECTS OF ADSORPTION ON INJECTION INTO GEOTHERMAL RESERVOIRS

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ABSTRACT

The effects of an adsorbing phase on the injection of liquid and eventual production of vapor from a low-porosity, vapor dominated geothermal reservoir was studied. The magnitude of delay caused by adsorption, diffusion partitioning, preferential partitioning, and permeability variation were compared. Results were then compared to measured tracer production data at the Geysers to determine the most likely delay mechanism for injected tracer at the Geysers.

A one-dimensional numerical model describing vapor flow in a porous medium in the presence of a sorbing phase was used to investigate the delay of injected tracer caused solely by the sorbing phase. An analytical model was used to describe delay effects due to diffusion partitioning of tracer from the vapor phase into the liquid phase. Properties of steam and tracer used in Geysers tracer studies were compared to determine the effects of preferential partitioning. Finally, a streamline model of a tracer study was used to determine the magnitude of permeability delays possible using permeability values measured at the Geysers.

It was concluded that adsorption alone has very little effect on the delay of injected tracer indicating that little recharge of the adsorbed mass occurs for a typical injection program at the Geysers. Diffusion partitioning was shown to have a larger effect on tracer delay than adsorption while preferential partition was shown to have no effect. Permeability variation was shown to have the largest effect on tracer delay. Tracer delay was shown to be approximated closely by known permeability variations even when adsorption and diffusion effects are ignored.

INTRODUCTION

Adsorbed liquid has long been known to significantly contribute to the mass stored in geothermal reservoirs. Measurements of adsorption isotherms in a range of porous solids and with a variety of fluids (Hsieh and Ramey, 1981) showed that adsorption can be significant in many geothermal and natural gas reservoirs. Application of measured adsorption data to volumetric analysis of the Geysers led to the conclusion that most of the initial mass in the reservoir was probably stored as an adsorbed liquid (Economides and Miller, 1985). Recent measurements of adsorption in Geysers core material indicate that at high pressures, the low porosity portions of the Geysers reservoir may be almost completely saturated by an adsorbed phase (Shang, et. al., 1993). These same measurements have also provided increasingly accurate descriptions of adsorption isotherms in the Geysers allowing increasingly accurate estimates of the effects of an adsorbed phase on reservoir performance for a wide range of pressures.

Due to pressure decline in the Geysers, injection programs have been undertaken in a number of areas in the reservoir. The purpose of these injection programs is to increase reservoir pressure, replace produced liquid mass, and ultimately increase production rate and the productive life of the reservoir. In order to assess the effectiveness of injection programs it is necessary to closely monitor the propagation of injected liquid in the reservoir. Monitoring of injected fluid may be accomplished either by monitoring production and pressure response in the reservoir or by introducing tracer along with the injected liquid and studying the production of the tracer. Production of the tracer provides information on the propagation of injected liquid in the reservoir.

In the Geysers, several tracer tests have been carried out and tracer production has been used to infer characteristics of the fluid propagation through the reservoir. In general, production of tracer at the Geysers has been characterized by long production times indicating some delay mechanism which significantly spreads the tracer concentration in the reservoir. It is the purpose of this paper to investigate the possible tracer delay mechanisms at the Geysers and to determine the size of delay of each. Specifically, the effects of adsorption on tracer delay are investigated to determine the influence of adsorption on injection programs at the Geysers.

INJECTION AT THE GEYSERS

Injection of cooling tower condensate began at the Geysers in 1969 with an injection to production ratio of 5 %. At initiation of the injection program, all injectate was cooling tower condensate. In 1980, fresh water injection, extracted from Big Sulfur Creek, was initiated into the Units 1-6 area. A second fresh water facility began providing water for injection in 1983. Fresh water injection hit a peak of 7 % of production in 1983 while total injection has stayed fairly constant at 20 - 25 % since the early 70's.

In general, two strategies have been used at the Geysers -- deep injection and shallow injection. In deep injection, outlying wells with deep steam entries are used as injectors in order to minimize downward channeling of liquid water to nearby wells. Effects of deep injection are often difficult to quantify and while short term benefits have been observed, it has been assumed that most of the benefits are long term (UNOCAL, 1992). The shallow injection strategy uses injection wells with steam entries higher than surrounding wells and relies on the vaporization of injected water as it channels toward surrounding production wells. Since breakthrough of shallow injectate is usually fairly rapid, benefits of shallow injection are generally short term. A number of injection programs have been undertaken at the Geysers. Some successful programs are outlined below.

Unit 14 injection, begun in 1983, and Unit 17 injection, begun in 1988 were both deep injection projects. The programs met with limited success, but both projects had some short term benefits.

Units 9-10 injection, initiated in 1992, was a shallow injection project, UNOCAL's first, and was expected to provide short-term benefits. Increased production was almost immediate, but problems with watering out of producers limited the program's success.

In September 20, 1989, the LPA injection program was initiated with injection into C-11 (Enedy, et. al., 1992). The LPA injection program was very successful and resulted in both recharge of liquid mass and increases in production. It demonstrated that injection can be used as a means to increase production from the Geysers reservoir and increase the efficiency of heat extraction from the reservoir.

Planning of future successful injection programs must rely on an understanding of the mechanisms which affect the flow of injected fluids. In this paper, the mechanisms which can delay the production of injected tracer are studied. By understanding the magnitude of tracer delay caused by several reservoir mechanisms, conclusions can be drawn about which characteristics of the reservoir must be studied to increase the efficiency of injection programs.

TRACER DELAY MECHANISMS

Mechanisms which may delay the propagation of tracer initially in the vapor phase are adsorption, diffusion partitioning, preferential partitioning, and permeability and flow length variations within the reservoir. Adsorption delays injected tracer when reservoir pressure is increased by injection and some of the injected mass is adsorbed and becomes immobile. Since tracer which resides in the vapor phase is also immobilized by adsorption, the rate of propagation of the tracer can be reduced. Another way in which the adsorption process reduces the propagation of tracer is by decreasing the rate of pressure decline in the reservoir. Since pressure drawdown is reduced by desorption of adsorbed liquid, pressure gradients in the reservoir are decreased and the flow velocity of vapor is also decreased.

Diffusion partitioning refers to the diffusion of tracer from the flowing vapor phase into the immobile adsorbed phase due to a concentration gradient. Diffusion partitioning occurs even in the absence of net mass transfer between the vapor and adsorbed phases. If diffusion is large with respect to convection of the vapor phase, concentration equilibrium between the two phases may be assumed instantaneous and the delay in tracer propagation due to diffusion can be calculated.

Due to the heterogeneous nature of Geysers reservoir material, permeability variations and differences in the flow path lengths between an injector and producer can also cause delays in the propagation of injected tracer. Estimates of flow path lengths for a given well pair and use of measured permeabilities in the Geysers can be used to calculate the probable spread in the production concentration of tracer due to these effects.

NUMERICAL MODEL

A numerical model was constructed to study the effects of adsorption on the propagation of injected tracer. A one-dimensional, linear flow model with constant cross section and rock properties was used to model adsorption effects. An implicit pressure, explicit saturation and temperature solution scheme was used. It was assumed that the adsorbed phase is immobile and that the only flowing phase is vapor. The numerical model was validated against known analytical solutions describing the flow of constant compressibility liquids and against analytical solutions for the flow of highly compressible liquids in the presence of a sorbing phase (Hornbrook, 1994). The numerical model was shown to match all analytical solutions exactly. Adsorbed phase properties were assumed to be identical to saturated liquid water which has been shown to be valid for the Geysers geothermal reservoir (Hornbrook, 1994).

EFFECTS OF ADSORPTION ON TRACER PROPAGATION

The purpose of this section is to delineate the effects of adsorption on tracer propagation in a porous media. In order to isolate the effects of adsorption, the effects of diffusion, preferential partitioning, and permeability variations were ignored.

Since the tracer considered in this report is tritiated water which behaves very much like water, the propagation of tracer was modeled as the propagation of a water component:

$$(1) \quad y_i^{n+1}T_{i+1/2}\left(p_{i+1}-p_i\right)^{n+1} - y_{i-1}^{n+1}T_{i-1/2}\left(p_i-p_{i-1}\right)^{n+1} - \frac{\Delta x}{\Delta t}\left[\left(y_{vi}\phi_i\rho_{vi}S_{vi}\right)^{n+1} - \left(y_{vi}\phi_i\rho_{vi}S_{vi}\right)^{n}\right] - \frac{\Delta x}{\Delta t}\left[\left(y_{ai}\phi_i\rho_{ai}S_{ai}\right)^{n+1} - \left(y_{ai}\phi_i\rho_{ai}S_{ai}\right)^{n}\right] + y_{inj}Q_{inj} - y_{prod}Q_{prod} = 0$$

where, the subscripts *a* and *v* refer to the adsorbed and vapor phases, respectively, the subscripts *i* refer to block numbering, and the superscripts refer to time steps in the numerical computation.

Adsorbed phase saturation is related to an adsorption isotherm by:

$$(2)\quad S_a = \frac{1-\phi}{\phi}\frac{\rho_r}{\rho_a} X(p/p_s)$$

where, X denotes the mass adsorbed per mass of rock at a given relative pressure (p/p_S).

In Eqn. 1, the pressures, saturations, and fluid properties determined at the end of each time step in the computation of mass transport of vapor are used to compute the mass fraction of injected mass in the vapor phase, y_V, in each block. In order to calculate the mass fraction in the vapor phase explicitly, a relation between the mass fraction in the adsorbed phase and in the vapor phase is needed. Since the goal in this section is to isolate adsorption effects, it was assumed that the mass fraction of injected tracer in the adsorbed phase is a weighted average of the fraction adsorbed at the old time step and the change in adsorbed mass over the time step:

$$(3)\quad y_a^{n+1} = \frac{y_v^{n+1}\Delta_t S_a + y_a^n S_a^n}{S_a^{n+1}}$$

By making the assumption that concentrations are a function of the adsorptive process and are not affected by diffusion, the effects of adsorption are isolated.

By varying initial and boundary conditions in numerical simulation of tracer flow, the range of adsorption effects on tracer propagation may be determined.

In the numerical simulations described below, the following form of the langmuir equation was used to describe adsorption isotherms:

$$(4)\quad X\left(\frac{p}{p_s}\right) = d\left[\frac{c(p/p_s)}{1+(c-1)(p/p_s)}\right]$$

where, c is the shape factor which determines the rate at which sorption occurs, and d is the magnitude factor which determines the maximum amount adsorbed at a relative pressure of 1.0.

Figure 1 shows a range of isotherms with d=1 and with c varying over the entire range of shapes considered in this research.

Figure 2 shows tracer profiles in a 4 m long simulated core for injection when steady state conditions have been reached in the core. Injection and production rates in the core were held constant for these experiments and steady-state conditions were allowed to develop. When steady state conditions had developed, the injection block pressure was approximately 7 MPa while the production block pressure was about 0.5 MPa. Clearly, when steady-state is reached, the presence of an adsorbed phase increases the propagation rate of tracer. This is due to the fact that the amount adsorbed at a given point in the reservoir is constant and, therefore, the area open for flow is reduced. This causes an increase in the tracer flow rate which is initially in the vapor phase.

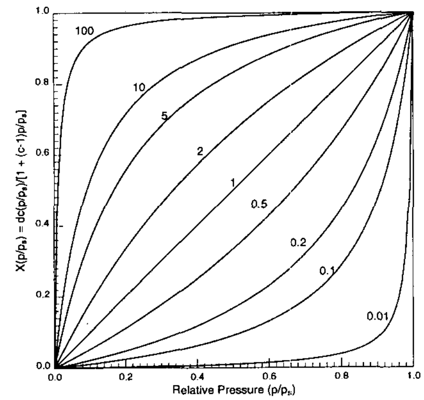

Fig. 1: Langmuir isotherms

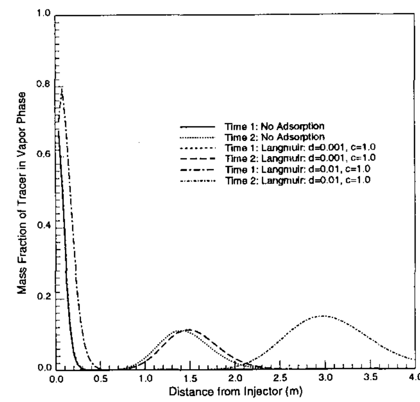

Fig. 2: Steady state flow

Figure 3 shows the tracer propagation in a core for conditions similar to those described above except that steady state conditions were not allowed to develop. In this case, the tracer begins moving faster due to a reduced flow area but eventually decreases in velocity due to adsorption of the vapor in which the tracer resides. The concentration of tracer when adsorption is occurring is also reduced due to loss of mass of the tracer to the adsorbed phase. Results shown in Figure 3 represent extreme conditions for the isotherm selected because the range between injection and production pressures is still large. Despite such large pressure differences, the tracer delay is shown to be only about 30%.

Figure 4 shows the rate of production of tracer injected into a 4 m long core. In this simulation, conditions approximating those at the Geysers were chosen to determine the likely effects of adsorption on tracer delay at the Geysers. Core temperature was set at a constant 300 C and injection was initiated at a relative pressure of 0.5. While the temperature is higher than that at the Geysers, the relative pressure is analogous. Tracer production is shown for injection with no adsorption, and for injection with adsorption for two controlling langmuir isotherms. In both cases, the magnitude factor is 0.01 which corresponds to an initial adsorbed phase saturation of 75%. This is an

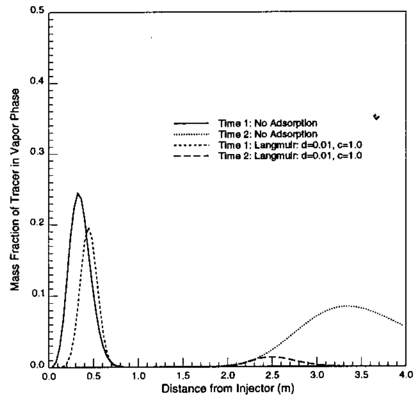

Fig. 3: Transient flow

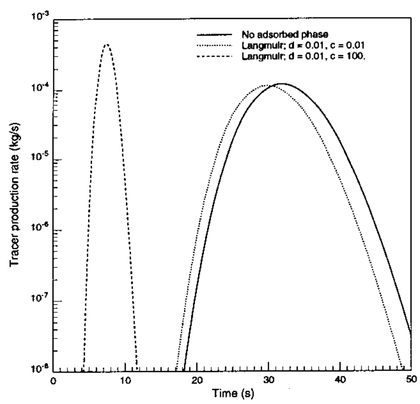

Fig. 4: Approximate Geysers tracer response

extreme case but is used to highlight adsorption effects. The shape factors used are 0.01 which is a concave up isotherm similar in shape to isotherms measured at the Geysers and 100 which represents a concave down isotherm for which desorption only occurs at low pressures.

It is shown in Figure 4 that the presence of an adsorbed phase increases the propagation of injected tracer. The reason for this increase in propagation is that the isotherms are nearly flat for relative pressure corresponding to initial injection into the core. Therefore, very little adsorption occurs to reduce the concentration of tracer in the vapor phase and very little pressure support is received by the production well to reduce the flow rate of vapor.

Based on these numerical experiments and others (Hornbrook, 1994), it was concluded that adsorption plays a very minor role in the transport of injected tracer in geothermal reservoirs. In the Geysers reservoir, tracer transport is probably increased slightly by the presence of an adsorbed phase.

EFFECTS OF DIFFUSION PARTITIONING ON TRACER PROPAGATION

Diffusion of tritiated water into the immobile adsorbed water phase was considered as a possible mechanism for delay of injected tracer. In order to understand the likelihood of diffusion partitioning, the relative sizes of the convective and diffusive fluxes must be computed and compared. The porosity in the Geysers and in other geothermal reservoirs is often very complicated (Fig. 5) with flow taking place mainly in the fractures and adsorbed phase storage occurring in the interparticle porosity (Gunderson, 1993). By comparing the convective flux computed using measured Geysers permeability and an estimated diffusive flux of tracer, it is possible to determine the range of permeabilities for which instantaneous diffusive equilibrium is likely.

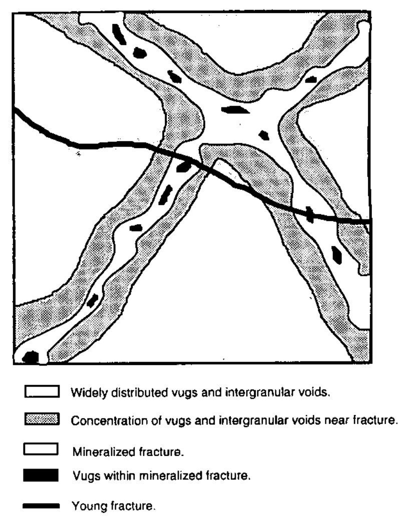

Fig. 5: Pore structure at Geysers (after Gunderson)

The diffusive flux of tracer is described by Fick's Law:

(5) $$v_{diff} = -D_{mol}\frac{\partial C}{\partial x}$$

where, D_{mol} represents the molecular diffusivity into a bulk phase. The diffusivity of tritium has been reported as 2.3×10^{-5} cm^2/s (Leap, 1992). In porous material, however, the diffusivity of a substance is decreased due to the tortuosity of porous matrix (Aris, 1975).

(6) $$D_{pore} = D_{bulk}\left[\frac{\phi}{a^2}\right]$$

where, a is the actual pore length per distance in the direction of diffusion. Assuming that the interparticle porosity is about 1% (Gunderson, 1993) and that the measure or tortuosity, a, is 2, the maximum diffusivity of tritiated water out of the vapor phase and into the adsorbed liquid phase was estimated to be 5.8×10^{-10} m/s. Assuming Darcy's law is a valid model for convective flux, the range of flow rates likely in the Geysers was found to be 2.9×10^{-5} to 2.9×10^{-9} m/s, Thus, except in the extremely low permeability regions of the reservoir, convective flux is significantly greater than the diffusive flux. Since is was demonstrated that, for at least some regions of the Geysers reservoir, diffusive partitioning is important, computations of delay caused solely by diffusion were made. An analytical solution for convection and diffusion of a tracer in the presence of an immobile phase has been constructed (Antunez, 1984). In the derivation, instantaneous concentration equilibrium between the phases was assumed. The expression for concentration as a function of location and time for constant injection of tracer into a porous media initially free of tracer is:

$$(7) \quad \frac{C(x,t)}{C_0} =$$

$$\frac{1}{2}\exp\left[\frac{xu_v}{K}\right]\operatorname{erfc}\left[\frac{x\sqrt{\dfrac{S_v\rho_v + S_a\rho_a}{KS_v\rho_v}}}{2\sqrt{t}} - \frac{\dfrac{u_v}{K}\sqrt{t}}{2\sqrt{\dfrac{S_v\rho_v + S_a\rho_a}{KS_v\rho_v}}}\right]$$

$$+\frac{1}{2}\exp\left[\frac{xu_v}{K}\right]\operatorname{erfc}\left[\frac{x\sqrt{\dfrac{S_v\rho_v + S_a\rho_a}{KS_v\rho_v}}}{2\sqrt{t}} + \frac{\dfrac{u_v}{K}\sqrt{t}}{2\sqrt{\dfrac{S_v\rho_v + S_a\rho_a}{KS_v\rho_v}}}\right]$$

In order to isolate the effects of diffusive partitioning, steady state flow conditions were assumed. When steady state flow conditions prevail, pressure at a given point in the reservoir is constant and, therefore, adsorption does not occur as vapor flows. This allows the study of diffusion into the immobile adsorbed liquid phase. In Eqn. 3, the vapor velocity, u_v is given by:

$$(8) \quad u_v = \frac{q_{sc}}{\phi S_v}$$

From Geysers data, the velocity of vapor was computed as about 8×10^{-6} m/s in the very low permeability regions of the reservoir where diffusion effects are large. From adsorption isotherm measurements (Shang, et. al, 1993) the saturation of adsorbed liquid was found to be about 3%. Saturated vapor and liquid properties were used in computations. The effects of diffusion partitioning on tracer propagation are shown in Figure 6. Tracer profiles with no adsorbed phase present and with an adsorbed phase saturation approximating conditions at the Geysers are shown. The effective velocity of injected tracer is shown to be reduced by about a factor of two due to diffusion into the adsorbed phase.

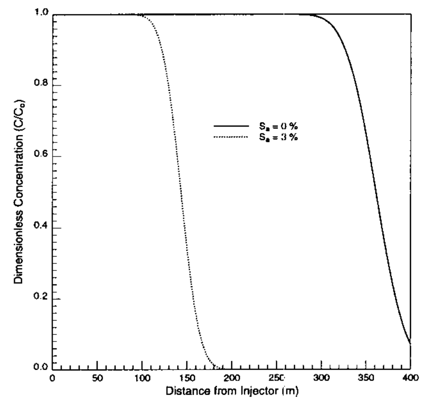

Fig. 6: Diffusion tracer delay

EFFECTS OF RESERVOIR HETEROGENEITY ON TRACER PROPAGATION

In order to investigate the effects of reservoir heterogeneity on the propagation of injected tracer, a model of the reservoir must be constructed which captures the flow characteristics of the reservoir. In this research, a stream tube model was constructed because it allows application of the linear flow model to complicated flow patterns. The DX-8 tracer injection test was modeled by assuming steady state flow between the injector and surrounding producers. Excess production was made up by introduction of surrounding imaginary injection wells. The reservoir was assumed to be homogeneous. Based on reported flow rates, and including the producers accounting for about 90% of recovered tracer, streamlines were generated for the DX-8 tracer study. Figure 7 shows developed streamlines for all wells included in the study.

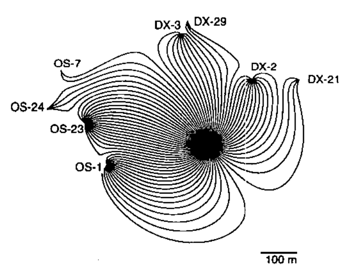

Fig. 7: Total DX-8 Streamlines

A single well pair was chosen to perform experiments on reservoir heterogeneity. The DX-8/OS-23 well pair was chosen because OS-23 accounted for approximately 34% of all produced tritium. The streamlines for the DX-8/OS-23 well pair are shown in Figure 8, and the tracer concentration in the produced vapor is shown in Figure 9. Concentration data are calculated from reported tritium production rate data (UNOCAL, 1991).

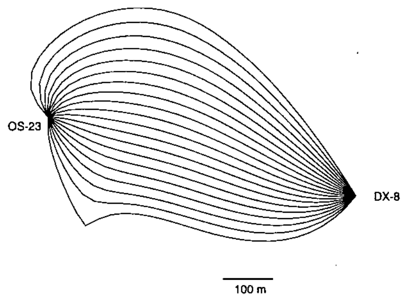

Fig. 8: OS-23/DX-8 Streamlines

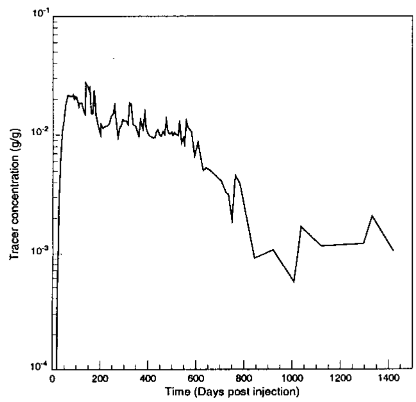

Fig. 9: Measured tracer concentration

Using the length of each stream tube shown in Figure 8 and the average cross-sectional area of each tube, a linear model of each tube was constructed. The permeability was varied in these stream tubes based on reported Geysers permeability. Slug injection of tracer was simulated and tracer concentration in the production block was monitored for each linear stream tube. By normalizing the initial breakthrough concentration of tracer to the measured value, and computing production tracer concentrations for all stream tubes, the effects of permeability and well separation on tracer propagation can be studied. Figure 10 shows a comparison of measured and computed concentrations. Production block concentrations for two of the stream tubes are shown to illustrate the range in tracer response possible for known Geysers permeabilities and well separations. The figure shows that even without adsorption or diffusion partitioning effects, the permeability and geometric variations present in the Geysers are sufficient to cause measured production delays in injected tracer.

Therefore, in designing injection programs, the communication between injection and production wells is the most important constraint with both diffusive partitioning and adsorption effects insignificant in comparison.

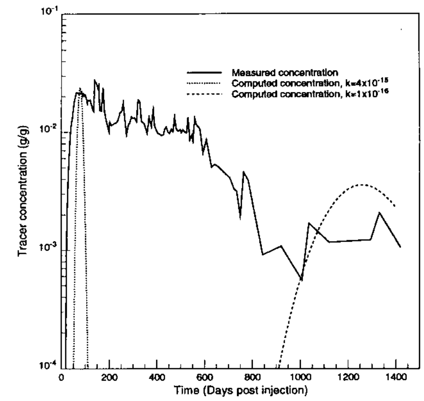

Fig. 10: Computed tracer concentration

CONCLUSIONS

Based on the results described above, the following conclusions about the effects of adsorption and other delay mechanisms on the propagation of injected tracer are:

1. The effects of adsorption on tracer propagation are small for adsorption saturations likely in geothermal reservoirs. For conditions likely at the Geysers, the presence of an adsorbed mass probably slightly increases the rate of propagation of injected tracer.

2. The effects of diffusive partitioning of tracer are large than those due to adsorption alone. In the Geysers, instantaneous concentration equilibrium does not occur in high permeability portions of the reservoir, but in low permeability regions diffusive partitioning may reduce tracer flux by as much as 50%.

3. Preferential partitioning due to differences in the boiling characteristics of the tracer and the carrying liquid does not occur to any measurable degree in the Geysers. The saturation curve for tritium is nearly identical to that of water.

4. Permeability and geometric variations, without any adsorbing or diffusive partitioning effects, is sufficient to explain tracer production characteristics at the Geysers. Thus, by far the largest factors in the design of injection programs are the reservoir permeability in the region of the injector and the separation between injector and producer pairs.

NOMENCLATURE

Variables

C	Mass Concentration	Dimensionless
D	Diffusivity	m^2/s
k	Permeability	m^2
p	Pressure	Pa
Q	Mass flow rate	kg/s
q	Volumetric flux	m^3/s

S	Saturation	Dimensionless
T	Transmissibility	kg/(m^2 Pa s)
t	Time	s
u	Velocity	m/s
X	Adsorbed amount	g-ads./g-rock
x	Distance	m
y	Mass fraction	Dimensionless
μ	Viscosity	Pa s
ϕ	Porosity	Dimensionless
ρ	Density	kg/m^3

Subscripts and Superscripts

a	Adsorbed phase.
bulk	Bulk phase.
diff	Diffusive quantity.
i	Counter for a block in numerical model.
mol	Molar quantity.
n	Time step counter in numerical model.
pore	Residing in a pore.
r	Rock.
s	Saturation conditions.
t	Denotes time operator.
v	Vapor phase.
0	Initial condition.

ACKNOWLEDGMENTS

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