SIMULATION OF RADON TRANSPORT IN GEOTHERMAL RESERVOIRS

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Introduction

Numerical simulation of radon transport is a useful adjunct in the study of radon as an in situ tracer of hydrodynamic and thermodynamic processes in geothermal reservoirs. A numerical model has been developed to assist in the interpretation of field experiments. The model simulates transient response of radon concentration in wellhead geofluid as a function of prevailing reservoir conditions.

The radon simulation model has been used to simulate radon concentration response during production drawdown and two flowrate transient tests in vapor-dominated systems. Comparison of model simulation with experimental data from field tests provides insight in the analysis of reservoir phenomena such as propagation of boiling fronts, and estimates of reservoir properties of porosity and permeability thickness.

Radon as an In Situ Tracer

Radon-222 is a ubiquitous in situ tracer for studying dynamic processes in geothermal reservoirs. It is produced continuously from the decay of its parent radionuclide, 1600-yr Ra-226 which is distributed throughout the reservoir formation. The emanation of radon gas from the rock matrix to the reservoir pore volume constitutes a constant, steady flux of radon to the geothermal fluids.

As a radioactive, gaseous, chemically-inert element with a useful half life of 3.83 days, Rn-222 is an ideal short-term, in situ tracer in geothermal reservoirs. The first-order decay property is a precise sink term in the reservoir, which combined with its emanation, results in measurable changes in radon concentration due to changes in physical, thermodynamic, and transport conditions in the reservoir during fluid production. As a chemically-inert rare-gas element, conservation of the tracer is assured due to lack of chemical retardation during transport through the reservoir formation. As a component of the noncondensable gases, radon is expected to partition between vapor and liquid phases of the geofluids. Phase partitioning becomes an important process in a simulation model of noncondensable gas transport in geothermal reservoirs.

Radon Transport Models

Analytical models which describe convective transport of radon with hydrodynamic dispersion through porous media are limited to steady-state solutions. A review of such solutions was made by Serdyukova and Kapitanov (1978) and by the National Bureau of Standards (1981). Analyses of radon transport in incompressible fluids for various flow geometry were made by Stoker and Kruger (1975), D'Amore et al. (1978), and Warren and Kruger (1979). A steady-state solution for compressible gases in radial flow was given by Sakakura et al. (1959). These analytical models applied to geothermal reservoirs require several simplifying assumptions, such as steady-state, isothermal, and single-phase conditions. To carry analysis of such systems further, numerical models are generally required.

Numerical models for single-phase radon transport have been developed by Clements and Wilkening (1974) for incompressible gas and by Edwards and Bates (1980) for compressible gas. These models have been applied to studies of the effect of atmospheric pressure variation on radon exhalation from ground surfaces and in mine cavities. Our model attempts to generalize the transport of radon by convection and diffusion with the emanation and decay aspects of radon, and the effects of gas partitioning between phases.

The radon transport model was formulated on the basis of the following set of assumptions:

1. Radon emanation into the pore volume is constant and independent of pore volume concentration.

2. The partial pressure of radon gas (at a molar fraction of the geofluid of the order of $10^{-16}$) is negligible.

3. Partitioning of radon gas obeys Henry's law, with local phase equilibrium in the reservoir.
Constant radon emanation implies small effect of change of thermodynamic conditions on the emanation (recoil/diffusion) processes in the rock. This assumption is supported by the observations of Satomi and Kruger (1982) that radon emanation was constant under experimental superheated conditions above a fractional saturation pressure of 0.5. The infinitesimal partial pressure of radon implies that radon transport can be resolved independent of the geothermal flow, and the assumption of local phase equilibrium implies that liquid and vapor terms can be combined.

The resulting equation for mass conservation includes terms for convective and dispersive transport, emanation source, and decay sink given by

\[ \frac{\partial}{\partial t} \left( \rho_1 C_{11} + \rho_v C_{v1} \right) = - \nabla \cdot \left( \rho_1 C_{11} \mathbf{V} \right) - \nabla \cdot \left( \rho_v C_{v1} \mathbf{V} \right) + \nabla \cdot D \frac{\partial}{\partial \mathbf{S}} \frac{\partial}{\partial \mathbf{S}} - \lambda (\rho_1 C_{11} + \rho_v C_{v1}) + E \] (1)

where

- \( \phi \) = formation porosity (m³/m³)
- \( \rho \) = fluid density (kg/m³)
- \( C \) = mass concentration (kg/kg)
- \( V \) = fluid velocity (m/s)
- \( S \) = volumetric saturation (m³/m³)
- \( D \) = coefficient of hydrodynamic dispersion (m²/s)
- \( \lambda \) = decay constant for radon (s⁻¹)
- \( E \) = emanation rate (kg/m³·s)

for the two phases: \( \mathbf{l} \) = liquid; \( \mathbf{v} \) = vapor

Solution of the equation is achieved by finite difference techniques, simplified by the decoupling of the radon transport equation and the geothermal flow simulation. In this solution, the reservoir hydrodynamic and thermodynamic conditions are determined from available reservoir simulators of the type described by Faust and Mercer (1979). For each time increment, the reservoir simulator calculates nodal values of fluid pressure, temperature, liquid and vapor saturation, density, and enthalpy. Values of temperature, saturation, and density, along with calculated liquid and vapor velocities, are used as input to the radon transport model.

The reservoir simulation model chosen for the radon transport model was developed by Zywoloński et al. (1979). This model was tested by the Stanford and New Zealand groups in the SGP Model Intercomparison Study (1980) and found to be in good agreement with other models tested.

The radon transport model has constructed as a finite difference model with (1) upwind (upstream) differencing incorporating a correction for numerical dispersion as described by Chaudhari (1973) for convection, and central differencing for hydrodynamic dispersion. The coefficients of hydrodynamic dispersion were assumed to be linear functions of fluid velocity, given by

\[ D = \phi L V + D^* \] (2)

where

- \( \phi L \) = longitudinal dispersivity (m/s)
- \( D^* \) = molecular diffusion coefficient (m²/s)

The time derivative is solved by numerical integration using fourth-order Runge-Kutta techniques. The solution is therefore explicit in form, second-order in space, and fourth-order in time.

The output of the model is the concentration of radon in the pore volume expressed as \((\rho_1 C_{11} + \rho_v C_{v1}) \) kg/m³. The liquid phase concentration required for the space derivative term is obtained from the total volumetric concentration by

\[ \rho_{1C_{1}} = \frac{(\rho_1 C_{11} + \rho_v C_{v1})}{(H - HS_1 + S_1)} \] (3)

where \( H \) = Henry coeff. (kg/m³) / (kg/m³)

The vapor phase concentration is obtained from the Henry Law equation

\[ \rho_{1C_{v}} = H \cdot \rho_{1C_{1}} \] (4)

Initial and Boundary Conditions

Reservoir radon concentration in an unexploited geothermal system is assumed to be in equilibrium with emanation from the formation rock. The volumetric concentration (in units of nCi/m³) is estimated by

\[ \rho_{1C_{1}} = \frac{E m_{R} (1 - 4)}{\phi} \] (5)

where \( E_{m} \) = emanation from rock (nCi/kg)
- \( \phi \) = rock density (kg/m³)

Emanation can be expressed as a mass flux (kg/kg·sec) by the conversion 1 nCi (radon) = 1.36 \times 10⁻²⁰ kg/sec.

The initial volumetric concentration is used to calculate the phase concentrations with equations (2) and (3). For saturation of 1.0 for either phase, the volumetric concentra-
tion for that phase is the total volumetric concentration of the reservoir.

The boundary conditions are Dirichlet type (concentration specified) for the outer boundary, and transmissive type for the inner (discharge) boundary of the dispersion term.

Simulations

The radon transport model is being used to evaluate data from a number of field experiments, including transient drawdown at the vapor-dominated fields at The Geysers, liquid-dominated reservoirs at Cerro Prieto, and the hot, dry rock experiment at Fenton Hill. This paper discusses the analysis of several drawdown transients at the vapor-dominated field at The Geysers observed by Stoker and Kruger (1975) and Warren and Kruger (1979). The model follows the transport characteristics of vapor-dominated reservoirs described by White et al. (1971) and Truesdell and White (1973). In vapor-dominated reservoirs, steam is produced from vaporization of water present in small pores in the formation. During exploitation, a boiling zone propagates out from the wellbore as pressure drops in the reservoir. Steam travels an increasing distance from its source to the wellbore with exploitation time. The radon transport model follows the response of emanated radon as a result of the vaporization process and its transport with the produced geofluid as the boiling zone propagates into the reservoir.

Vapor-Dominated Model

The radon transport model is based on radial flow in a homogeneous reservoir, in the same manner as well test simulation in vapor-dominated reservoirs as discussed by Moench and Atkinson (1978) and Moenoh (1980). Reservoir properties for the homogeneous reservoir used in the simulation are given in Table 1. The property values are in the range reported by Pruess and Narasimhan (1982) for the Geysers reservoirs. Our value for pressure drops in the reservoir does not have a source or sink in the reservoir.

The simulation of radon transients was run with radon concentration at the wellhead assumed equal to the concentration at the wellbore product node in the model mesh. Figure 1 shows the spatial response of pressure, saturation, mass flow, and radon concentration, with simulation outputs at 1.2, 12, and 36 days during a constant rate drawdown. For comparison, the concentration of a nonradioactive, conservative component of the noncondensable gases is shown for the same times. The conservative component has the same initial concentration as radon and the same Henry's law partition coefficient, but the pressure responses of this simulation show a drawdown extending into the formation. With time, the pressure drawdown results in vaporization, with a gradual decrease in liquid saturation. The mass flux responds to the outward propagation of the boiling zone during exploitation, with steam traveling to the wellbore from further in the formation.

The comparison of the response of radon concentration to the conservative noncondensable gas shows the influence of its source and sink properties on reequilibration to changing thermodynamic conditions. Radon concentration decreases near the wellbore at early drawdown time of 1.2 days by dilution of the original pore volume steam with newly produced steam from vaporization of liquid water of low radon content. The response of the conservative gas tracer is the same as radon, also due to the dilution process. After 12 days of drawdown, however, the distribution of radon concentration is different from that of the conservative gas. The radon concentration is observed to increase over the 12-day period while the conservative gas concentration remains constant. The increase in radon concentration is attributed to the emanation of radon into the steam over a larger reservoir volume as the travel distance increases, whereas the conservative gas component which does not have an emanation source remains diluted in

<table>
<thead>
<tr>
<th>Formation Properties</th>
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<tbody>
<tr>
<td>Porosity n &lt; 0.10</td>
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<tr>
<td>Rock Density ρ &lt; 2300 kg/m³</td>
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<tr>
<td>Rock Specific Heat C &lt; 1000 J/kg °C</td>
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<tr>
<td>Rock Thermal Conductivity K &lt; 0.0 w/m °C</td>
</tr>
<tr>
<td>Reservoir Thickness h &lt; 500 m</td>
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<tr>
<td>Matrix Porosity k = 1 x 10^-16 m² - 1 x 10^-13 m²</td>
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<tr>
<td>Rock Radon Emanation E &lt; 0.005 - 0.015/kg</td>
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<tr>
<td>Dispersivity α = 1 m</td>
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<th>Initial Conditions</th>
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<tr>
<td>Liquid Saturation S_l = 0.25, 0.50</td>
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<td>Temperature T = 241°C</td>
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<tr>
<th>Production</th>
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<tbody>
<tr>
<td>Wellbore radius r_w &lt; 0.12 m</td>
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<tr>
<td>Skin S &lt; 4.50</td>
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<tr>
<td>Effective Wellbore Radius r_w* = r_w - S = 10 m</td>
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<tr>
<td>Production Rate 10 kg/sec = 36 kg/sec</td>
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TABLE 1

PARAMETERS FOR NUMERICAL SIMULATION
concentration. At 36 days, the boiling zone has progressed further into the formation, and the radon concentration continues to increase, but at a decreasing rate. Because of the 3.83-day half life of Rn-222, equilibrium is expected between its increased decay during the longer travel time to the wellhead and its increased concentration due to the expanding emanation volume. The conservative gas component concentration remains constant.

To estimate the usefulness of the model to the design of additional field experiments for evaluating reservoir properties such as permeability thickness, it is necessary to obtain experience on the sensitivity of model output to model input parameters. For this purpose, a second simulation was run with variations in permeability, initial liquid saturation, and production rate. The results of well node radon concentration as a function of log (time) are shown in Figure 2. The results show three generally distinct regions: (1) essentially linear decrease at early time (0 to 0.4 d); (2) a steady-state period (0.5 to 1 d); and (3) a period of almost linear increase (after 4 d). The two linear periods suggest a first-order dilution process for the early period and a first-order build-up during the latter period, consistent with the propagation of the boiling zone into the reservoir. These observations are in accord with the numerical results of Moench and Atkinson (1978) which show a linear relationship between dimensionless pressure drawdown (as $p^2$) and log (time). The form of pressure response governs the growth of the vaporization zone and changes in fluid density. Both of these parameters affect the radon concentration.

The effect of permeability is noted in Figure 2a. The data show a strong dependence of decrease in permeability on initial dilution at early time. The large dilution results from the steep pressure gradient near the wellbore with localized boiling. At higher permeability, where the pressure response is more rapid, boiling becomes more distributed. The increases of radon concentration at later time appear somewhat symmetric. The slopes of the two lower permeability values seem to increase with time. This may be due to the effects of fluid compressibility. With increased pressure drawdown, the resulting steam has a lower density and therefore greater specific volume exposing a greater rock volume for radon emanation to the steam.

The data in Figure 2b indicate that radon concentration does not appear to be highly sensitive to initial liquid saturation. This observation is surprising in that it was anticipated that the rate of boiling zone propagation from the well would be a function of the initial liquid saturation. Perhaps its influence is offset by radon enrichment by phase partitioning from liquid water to steam.

The results in Figure 2c show that radon concentration is influenced by production rate. The dilution rate at early time is more strongly dependent on production rate compared to the growth rate at later times. The factors influencing these observations are not clear at this time, and the results of the simulation support our prior conclusions that multiple flowrate drawdown tests with radon as a mass tracer may be a useful method for reservoir evaluation in conjunction with pressure drawdown tests.

Simulation of Field Experiments

Simulations of two types of radon drawdown experiments have been reported. There are short-term (8-12 hours) tests reported by Stoker (1975) and the longer-term (75 day) drawdown reported by Warren (1980). Stoker ran several short tests during well production testing from bleed-rate shutin, whereas Warren ran a long-term production test that included two radon transients following rapid flowrate change.

A. Short-term Tests

Figure 3 shows the simulation results of the short-term drawdown test of Stoker for the repeated flow of 8 to 12 hours following shutin for periods of 12 to 16 hours over a three-day period. The simulations show good agreement with the observed data. The early decrease in radon concentration by dilution from near wellbore boiling is readily observed, especially in the second transient, when early wellhead sampling was achieved. The model shows enrichment of radon during shutin, indicative of the condensation of steam with pressure build-up near the well. The sensitivity of the model to these effects suggests that radon measurements of cyclic production testing of new wells can markedly assist in early reservoir evaluation.

The results of the simulations of three drawdown tests by Stoker in well IV-C and IV-D at The Geysers are given in Figure 4. For these simulations, a permeability thickness of 20 darcy-m was used, close to the value of 6.9 darcy-m reported by Ramsey and Gringarten (1976) for a well in another part of The Geysers field. The effective wellbore radius of 5 m used in the simulation is equivalent to a skin factor of ~ 3.8, in the range reported by Economides and Fehlberg (1979) and Pruess and Narasimhan (1982). The three drawdowns show similar behavior, linear drawdown to pseudo steady state achieved at approximately 6 hours. The slopes are reasonably uniform. The difference between the two experiments in well IV-C may be attributed to time period of about one month between tests. One possibility is a change in near-wellbore permeability. Economides and Fehlberg (1979) suggested that an observed increase in negative skin with production may result from cleanup of well
damage and fractures. The results of the simulation (given by the dashed line) shows a good fit between the actual data for a similar production rate. The radon emanation coefficient of 0.008 mCi/kg is in the range of laboratory measurements from Geyser rock cores. The slope of the early period dilution is similar to the slope of the three tests, and the approach to steady state is also similar. The agreement for the two wells is rather good considering wells IV-C and D are 1.5 miles apart and the difference in steam entry levels was 360 ft. The agreement also suggests that the dilution process is the likely one to explain the observed data. Wellbore storage unloading is not considered important with the wellbore partially filled with steam during bleed-rate production. Approximately 40 wellbore volumes were produced before first samples were collected.

B. Long-term Drawdown Experiment

The long-term drawdown experiment conducted by Warren (1980) was a 75-day flow experiment with two changes in flowrate to observe the radon transients. The data reported by Warren show a growth in radon concentration during the first 30-day period of stabilizing flowrate, a transient decrease over the next 27 days at reduced flowrate, and a rise when the original flowrate was restored. Although the radon data showed a strong cyclic variation over a few-day period, Warren and Kruger (1979) indicated by cyclic averaging that the large fluctuations could be consistent with a boiling process with steam transport in cyclic bursts. Radon in higher concentration can be produced from small pores with larger fractional emanation and mixed with steam from larger pores of lower emanation.

Figure 5 shows the results of the simulation of the constant rate build-up period in relation to the observed data. The simulation was run with a permeability of $2 \times 10^{-18}$ m², thickness of 500 m, effective wellbore radius of 10 m, representing an equivalent skin value of -4.5, and initial liquid saturation value of 50%, both within realistic values at The Geyser Reservoir. The model reproduces the data fairly well.

A test of the simulation model occurred during the radon transient period after the wellhead flowrate was reduced instantaneously. Figure 6 shows that the simulation results, based on a homogeneous radial flow reservoir, produce the opposite results from those observed. The model predicts a sharp rise in response to the partial shut-in with a gradual attenuation to a higher value than before shut-in, whereas the observed transient is a continuous decrease in radon concentration. The increase in radon concentration predicted by the model for the flowrate change can be attributed to three effects: (1) a lower degree initial dilution in the zone of vaporization; (2) enrichment of radon in the steam phase as condensation occurs; and (3) increased residence time in the reservoir resulting in a greater approach to equilibrium radon concentration.

The change in flowrate could also have a large effect on radon concentration if the reservoir is inhomogeneous. Kruger et al. (1977) and D'Amore et al. (1978) suggested the decrease in wellhead radon concentration following rapid flowrate reduction to the longer decay period during transport through a reservoir with low radon emanation. Warren and Kruger (1979) also interpreted the observed increase in radon concentration in the long-term drawdown as production of steam from successively smaller and smaller pores, with larger fractional emanation values.

The two possibilities suggested that a dual-block model might be more representative of The Geyser Reservoir than a homogeneous radial model. The two-block model proposed is a combination of an inner block of highly fractured, permeable, low liquid saturation, and low emanation, connected to an outer block of lower permeability, high liquid saturation and higher emanation. During exploitation, withdrawal occurs first from the high permeability fissure block with later production of steam originating from the outer block.

The data of Warren (1980) was evaluated with a two-block model in which three important parameters of the two blocks were varied: (1) emanation coefficient, (2) block volume, and (3) liquid saturation. Figure 6 shows the match between the simulation and the observed data. In this simulation an emanation coefficient in the fissure block which is a factor of 10 lower than in the outer reservoir is required for the match. This factor can be supported from the work of Sammis et al. (1981) who observed lower emanation with increased permeability in granite cores.

The match also required essentially no liquid saturation, $S_1 = 0.005$, in the fissure block. This requirement can be supported from the model of Truesdell and White (1973) and simulations of Pruess and Narasimhan (1982) for steam production from fractured systems based on low or zero liquid saturation. The reservoir volume of the fissure block is of the order of 3.4 x 10⁷ m³. In a reservoir of 20-acre well spacing, the corresponding reservoir thickness would be 425 m. This large fissure block pore volume of low emanation is needed for efficient decay of radon during transport from the outer block to the wellbore. Thus as flowrate is reduced and residence time increases, the decay or radon also increases, resulting in the observed lower radon concentration. The dual block simulation shows radon concentration reaching a steady-state value after production from the outer block has been established. Radon concentration should remain
fairly constant with further constant rate drawdown.

Physical factors that are more difficult to simulate can also be important. For example, Holub and Brady (1981) show from experimental studies of radon emanation from stressed rock that temporary increases in emanation result from applied uniaxial stress. Emanation returns to original values when the stress is removed. In the reservoir, changes in pressure resulting from changes in flowrate could in turn produce temporary changes in emanating power from the reservoir rock. Another possibility is a multi-layered system of dual permeability where the flow from each layer responds to pressure changes in the formation. A further effect may be from water adsorption. Herkelrath et al. (1983) indicated that adsorption of water at superheat conditions could modify the pressure response of the formation.

Other suggestions for improvement of the current simulation model includes review of the assumption of thermodynamic equilibrium between rock and fluid phases. If thermodynamic equilibrium is not achieved, temperature changes in the fluid phase would be greater than predicted by the model. Since solubility of radon in the liquid phase is temperature dependent, partitioning of radon during evaporation/condensation processes would change, with corresponding changes in radon concentration.

Conclusions

The simulation model of radon concentration in fluids produced from vapor-dominated reservoirs appears to follow adequately the results observed from field experiments at The Geysers geothermal field for both short-term and one long-term drawdown. The simulations based on appropriate values of input parameters, such as reservoir permeability thickness, agree well with the values determined by traditional reservoir engineering practices.

The results support the model of an expanding zone of vaporization during exploitation, resulting in corresponding increases in radon concentration. Simulation and field experimental results are in good agreement for constant flowrate drawdown tests. Simulation of two-flowrate tests resulted in the need to introduce a two-compartmental model with differing average properties in the two zones to reach agreement between simulated and observed results. The concept of a two-zone reservoir should be explored in greater detail.

References


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Vapor Dominated Drawdown
Radon Response - Radial Geometry

Figure 1. Spatial and temporal response for a constant rate drawdown.

Figure 2a, b, c. Sensitivity to permeability, saturation, and flowrate.
Figure 3. Comparison of model simulations to field transients during a cyclic drawdown experiment at The Geysers.

Figure 4. Response of radon concentration versus log (time) in short-term drawdown experiments at The Geysers.

Figure 5. Comparison of model simulation to radon build-up response in a 38-day constant rate drawdown experiment at The Geysers.

Figure 6. Dual-block model and homogeneous radial model responses to a two-rate drawdown test at The Geysers.