RADON TRANSECT STUDIES IN VAPOR- AND LIQUID-DOMINATED GEOTHERMAL RESERVOIRS

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INTRODUCTION

Radon transect analysis involves short-term sampling of wells across a geothermal reservoir to examine structural and thermodynamic properties of the reservoir. In these studies, two natural gaseous components of the produced geofluids are measured: (1) the radioactive isotope, radon-222 which decays upon release from the host rock with a half-life of 3.83 days; and (2) the non-radioactive compound ammonia, which appears to be produced continuously in geothermal fluids. The information sought in these studies include data on the spacial and temporal behavior of the geofluids in relation to the structural and thermodynamic conditions in the reservoir. Factors that can effect the relative composition of these two natural components include their relative solubilities, partitioning functions under cycles of brine evaporation and condensation, radioactive decay (radon only), and chemical reactions (ammonia only).

The use of radon as an internal tracer of geofluid transport has been well documented (e.g., Stoker and Kruger, 1975; D'Amore and Sabroux, 1976). Kruger, Stoker, and Umaña (1977) noted the large difference in radon concentration between liquid and vapor-dominated geothermal reservoirs as well as significant variations between neighboring wells in one formation and temporally within a single well. Models of the relationships between radon concentration and flowrate have been described (e.g., Stoker and Kruger, 1975; D'Amore and Sabroux, 1976; Warren and Kruger, 1979). These models considered linear, radial, and conical flow geometry with radon release from uniformly deposited radium in the host rock flowing with the brines or steam through a reservoir of uniform properties. In the conical model of Warren and Kruger (1979), radon in vapor-dominated geothermal reservoirs is assumed to boil out with steam production at a boiling front in the reservoir, with radon decay during transport through the steam reservoir to the well plus an accumulation of radon from the reservoir rock along the transport path. Thus the radon concentration at the wellhead is dependent on a number of parameters describing the release and transport of the radon with the geofluids.

Radon concentration in geothermal fluids under steady flow conditions have been shown by Stoker and Kruger (1975) and D'Amore et al (1978) to depend on the release parameters,

$$C_s = \frac{E_m \rho_r}{\phi \, \rho_f} \qquad (1)$$

where C_s = mass concentration of radon, nCi/kg rock

F_m = emanating power, nCi/kg rock

ρ_r = rock density, kg/m^3

ρ_f = fluid density, kg/m^3

ϕ = porosity, m^3/m^3

For constant rock density at the producing pressure, the concentration of radon is expected to be inversely proportional to the fluid density. Thus the great difference in density of water and steam in pore volumes is consistent with the observed difference in radon concentration in liquid and steam geothermal fluids.

Warren and Kruger (1979) reported the results of flowrate transient experiments in vapor-dominated reservoirs. The observed transients in radon concentration following instant changes in flowrate were described by the model of boilout, transport, and radon decay and accumulation with respect to the steam phase. It was noted that the assumption of constant radon emanation during the flowrate (and pressure) change might not be valid. Macias, Semprini, and Kruger (1980) observed significant changes in radon emanation with changes in the geothermal fluid and the thermodynamic conditions in the reservoir. The method of transect analysis was developed to bridge these two types of study. In order to separate the changes due to time properties of the release and transport, during which radon is undergoing continuous radioactive decay, a non-radioactive component of the non-condensible gases is measured simultaneously. Analysis of these two components may be helpful in distinguishing between changes in radon concentration due to changes due to transport phenomena during production. This communication describes the transect analysis conducted at the vapor-dominated reservoirs at The Geysers in California and the liquid-dominated reservoirs at Cerro Prieto in Baja, California.

TRANSECT EXPERIMENTS AT THE GEYSERS

Three radon transect analyses have been completed at The Geysers; two of them (I and II) along a line of wells in the older producing zones, and the third (III) in a newer producing area across Big Geyser Creek. Ammonia measurements were also made in transects II and III.

(a) General Observations

The results of transects I and II are shown together in Fig. 1. The two experiments show similar profiles in that the radon concentration decreases from left to right along the transect, indicating either longer transport times in the right part of the field or greater accumulations in the left part of the field. Linear regression analysis of radon concentration as a function of flowrate along the transect showed a negative correlation of -0.61, indicating radon concentration to be either inversely related to flowrate or that radon is accumulated by either increased emanation or enrichment by condensation processes.

The concentration profiles of radon and ammonia for transect II are shown in Fig. 2, in relation to the structural cross section of the reservoir. The concentration gradients of the two components appear similar, with an abrupt change at the location of the indicated faults. Although the radon-ammonia ratio is highly correlated along the transect (with a linear correlation coefficient of 0.97), the average ratio is significantly different on either side of the faults. The eight wells on the left have a mean ratio of 0.08±0.01 whereas the seven wells on the right have a mean ratio of 0.15±0.06. If the ammonia concentration is conservative across the transect, the data would indicate that radon is undergoing depletion in the left part of the field and enrichment on the right part. Another way to express this difference is to assume that radon has a longer transport part on the left or that ammonia undergoes a process of greater accumulation. These two experiments have produced a number of possible processes that may be operative at this field:

(1) a physical or chemical process for addition or depletion of ammonia with a rate constant suprisingly similar to the 3.83 day half-life of radon-222,

(2) a common source of both components in the host rock with the concentrations dependent primarily on emanation and reservoir fluid properties,

(3) changes in the degree of saturation of the enrichment of the non-condensible gases in various areas of the field,

(4) enrichment processes such as condensation within the steam zone of the reservoir in which case both components would be enriched as functions of their partition coefficients.

Although possibility (1) cannot be ruled out at the present time, no physical or chemical process for ammonia with a rate constant of approximately 3.8 days is apparent. Evaluation of possibility (2) awaits further clarification of the changes in emanation with changes in reservoir properties and additional chemical information of the host rock. Possibility (3) represents enrichment processes such as the Raleigh condensation process proposed by D'Amore and Truesdell (1980), where gas components are enriched. In such processes the ammonia concentration reflects long-term enrichment while the radon concentration reflects saturation conditions. If this possibility predominates, the data would indicate that higher radon concentrations occur where greater amounts of vapor are present, suggesting a change in degree of gaseous saturation. In this case, wells in the left part of the transect are producing from shallower zones with greater vapor content. In possibility (4), condensation and vaporization cycles would concurrently enrich both concentrations, but the ammonia concentration would not be as time dependent as the radon concentration, which would reflect only the latest 10-30 days of such processes.

(b) Thermodynamic Relations

Reservoir conditions play an important part in wellhead concentrations of radon and ammonia. Downhole pressures in transect II and III vary over a significant range: from 100 to 380 psia for transect II; and from 190 to 310 psia in transect III. Equ. (1) notes the radon concentration to be inversely dependent on the fluid density. Linear regression analysis was made of the radon concentration as a function of specific volume of the reservoir fluid for the reported downhole pressures. Fig. 3 shows a correlation coefficient of 0.78 and a slope suggesting an inverse relationship between radon concentration and fluid density as given by Equ. (1). Similar results were obtained for the regression analysis of the ammonia concentration data, indicating that the ammonia is released from the formation rock by the same diffusion processes responsible for radon release.

The effect of changes in reservoir pressure on the partitioning of the two gaseous tracers between the brine and vapor phases must be considered. It is not clear whether the changes in partition coefficients of radon and ammonia between brine and steam are sufficient to result in the observed radon-ammonia ratios. Variations in emanation of radon with changes in pressure and temperature under controlled model reservoir conditions were noted by Macias, Semprini, and Kruger (1980). Further experimental data on their emanation is required to further evaluate this process.

TRANSECT EXPERIMENTS AT CERRO PRIETO

Two transect analyses have been completed at Cerro Prieto to evaluate the transects in terms of the structural features of the field and the thermodynamic conditions in a liquid-dominated reservoir. The structural features have been described by Vonder Haar and Howard (1980). The data were grouped into the four subset transects shown in Fig. 4, which cross some of the given faults and were examined for the changes in thermodynamic conditions over the field. A preliminary indication that radon concentration was related to fluid enthalpy was noted by Horne and Kruger (1979) in a study of radon emanation along the Waiora fault at Wairakei, New Zealand.

A total of 23 wells were sampled at Cerro Prieto during the two transect experiments and the enthalpy of the fluids ranged from 1230 to 2360 kJ/kg, representing a range in produced fluid mixtures from all liquid to 70% vapor at a reservoir temperature of 290°C. The corresponding wellhead radon concentrations ranged from 0.20 nCi/kg in the low enthalpy wells to 3.6 nCi/kg in the highest enthalpy well.

An analysis of the data was attempted by modifying Equ. (1) to represent the contributions to the concentration from the two fluid phases:

$$C_T = X \frac{E_v \rho_r}{\phi \rho_v} + (1-X) \frac{E_1 \rho_r}{\phi \rho_1} \qquad (2)$$

where X is the steam saturation. The enthalpy of the two phase mixture is given by

$$h = Xh_v + (1-X)h_l \tag{3}$$

A regression analysis of the concentration-enthalpy data, shown in Fig. 5, was made to examine the linearity between these two parameters. A linear relationship, with correlation coefficient of 0.80, is implied, but is highly influenced by the high radon-high enthalpy of well M-45. An equilibrium volumetric radon concentration of 168 nCi/m^3 pore volume was estimated for the observed average radon concentration of 0.20 nCi/kg for the low enthalpy wells having production of all liquid with density of 840 kg/m^3. The calculation, however, was made with the assumption that the volumetric concentration was identical for both phases, which is probably incorrect according to the observations of Macias, Semprini, and Kruger (1980) that emanation changes with pore fluid density.

The dashed lines in Fig. 5 represent reservoir temperatures of 280°C and 320°C. The regression line of the data represents a reservoir temperature of 290°C, in good agreement with Na-K-Ca geothermometer estimate given by Mãhon et al (1978). Analysis of the four subset transects shown in Fig. 4 shows increased detail in examining the dependence of radon and ammonia concentrations on the enthalpy as steam saturation of the produced fluids. The correlation between radon concentration and fluid thermodynamic conditions indicate that radon monitoring may provide information on changes in the field. For example, if the relations measured to data are reliable, the data indicate a decrease in reservoir temperature in the southern area of the field with exploitation while temperatures have remained high in the eastern area. The data may also be indicating that phase separations are occurring in parts of the field such that equilibrium is achieved in both phases. Further measurements of radon should corroborate the initial suggestions that wells in the north central area flow primarily as liquid with evidence of two-phase conditions in the area of well M-27, and that flow is predominantly two-phase in the south-central area near wells M-45, M-48, and M-84.

CONCLUSIONS

Results to data are confirming the development of radon transect analysis to study the structural and thermodynamic features of vapor- and liquid-dominated geothermal reservoirs. The three experiments conducted at the vapor-dominated fields at The Geysers have raised several interesting questions concerning the source and transport of various gaseous components of the produced geofluid. Pressure variation appears to play an important role in determining the emanation of radon (and ammonia) from the formation and the transport of these gases during production may be influenced by the thermodynamic changes in the steam transporting them to the wellhead. Changes in structural regime in the old area of The Geysers may be observed by these measurements.

Measurements at Cerro Prieto are indicative of liquid-dominated reservoirs. Here, current measurements do not show that radon concentrations are influenced by structural features. The radon (and ammonia) concentration appears to be influenced primarily by the thermodynamic state of the one- or two-phase geofluid. The use of radon and ammonia as internal tracers to two-phase reservoir during production appears to be warranted.

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