RADON TRANSECT AND EMANATION STUDIES

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Radon transient analysis has been demonstrated as a means of examining mass transport in geothermal reservoirs (Warren and Kruger, 1979). The relationships between observed wellhead radon concentration and emanating power, flowrate, and reservoir volume were explored by Stoker and Kruger (1975), using linear and radial flow conditions, and D'Amore and Sabroux (1976) for the extremes of pipe flow and diffuse flow through the reservoir. Warren and Kruger (1979) extended the analysis of radon concentration transient with abrupt change in flowrate using a conical flow pattern in vapor-dominated systems characterized by a constant boiling front at depth. Analysis of several test cases showed for single flowing wells that the model provided reasonable estimates of reservoir pore volume and permeability-thickness. However, it was also noted transients in multiple flowing well systems could be more difficult to interpret because of the effects of (1) interference of flow between wells when only one is partially shut in, and (2) changes in emanating power of the reservoir formation due to the resulting pressure changes.

The observed variations in radon concentration among neighboring wells in a geothermal field suggest that the steam and radon sources in the system are not uniform. Three major parameters that affect the radon concentration in the produced steam are (1) the radium distribution along the flow path, (2) the emanating power of the formation, and (3) the transit time from source to wellhead. Experimental data to date show that radon concentration is not determined by near well radium deposits. Warren and Kruger (1979) discussed the effects of radium diffused through the reservoir and contained below a boiling-water table. Current efforts in our program have been focused on two types of experiment to amplify the radon transient technique: (1) Radon transect analysis to examine the distribution of steam "age" in relation to the 3.83-day half life of radon, and (2) Radon emanating power to relate concentration to the properties of the reservoir and geofluid.

Radon Transect Analysis

The technique involves short-term sampling along a line of geothermal wells across areas having structural significance in the reservoir. If the age distribution of the steam or hot water in the reservoir is in the range measurable by the decay period of the 3.83-day Rn-222 internal tracer, data on the flow regime may be ascertained. To show that observed variations in radon concentration are due to transport time and not to other physical effects, stable chemical components of the noncondensable gases are also measured. The radon concentrations are evaluated with respect to wellhead pressure, temperature, and flowrate.

Several radon transect samplings have been completed. Two were obtained during 1977 and 1978 in two areas of The Geysers geothermal fields. In 1977 a survey of wells in one area showed radon concentrations ranging from 4.9 to 18.9 nCi/kg. In 1978, a transect across 16 wells in another area showed radon concentrations ranging from 10.5 to 87.4 nCi/kg. Both tests involved sampling across suspected structural features. The distribution of concentration across these features are currently being evaluated with the reservoir operator.

During 1979, radon transect experiments were conducted in three types of geothermal reservoir: (1) a repeat test in one of the two areas at The Geysers, (2) an initial transect at the flashing fields at Wairakei, New Zealand, and (3) an initial transect across the major production zone at Cerro Prieto, Mexico. Analysis of this last test is not yet completed. The results of the first two show several interesting features.

(a) Radon Transect at The Geysers

The 1979 transect at The Geysers involved sampling 15 wells in a line parallel to one of the original transects. Some of the wells in the area were no longer in production. Two significant changes in experimental procedure were introduced: (1) samples were taken simultaneously for analysis for ammonia and total noncondensable gas content, and (2) the sampling method for radon was double stage condensation introduced into our program this year. Analytical procedures for radon measurement have been reported previously. Ammonia, stabilized during sampling as NH_4^+, was determined by the standard Kjeldahl method.

Figure 1 shows the results of the radon transect analysis. The marked gradient in concentration of all three components along the 15-well transect is quite apparent. The gradient for radon agrees well with the gradient observed in the 1978 test. The extent of linear correlation between the radon and ammonia gas content is evident in Figure 2. The correlation coefficient of 0.97 indicates that both components have a similar region of origin in the reservoir and are conservative in transport.

Except for the unlikely coincidence that ammonia undergoes a destructive chemical reaction during transport with reaction periods similar to the 3.83 day half life of radon, the radon concentration gradient across the transect cannot be attributed to radioactive decay. Several other processes affecting radon and ammonia similarly are possible. One of these is the suggestion by White, et al (1971) that the gases undergo isobaric distillation during transport to the wellhead. The constant radon/ammonia ratio further suggests that this process occurs rapidly compared to 3.8 days. A second process might be an offsetting increase in radon emanation due to processes that result in greater noncondensable gas content. A third process might be an isotropy in organic substances containing greater uranium content. The net result would be increased radon emanation accompanied by increased ammonia release by anaerobic decomposition. These experimental results have opened a new avenue of inquiry in evaluating geothermal fluid sources and transport processes.

(b) Radon Transect at Wairakei, New Zealand

An informal radon transect experiment was conducted with Prof. Roland Horne during his stay at the University of Auckland. An initial survey of two Wairakei wells sampled in March, 1979 showed radon concentrations of 3.4 and 139 nCi/kg, respectively, after cyclone separation of the vapor phase. These divergent results led to a transect study in which a series of samples were taken in May and August across the major Waiora fault, a well-studied geologic structure in the production zone. The two series of samples involved 12 wells along the Wairora fault within the 260°C maximum temperature isopleth parallel to the fault and 3 wells normal to it.

Figure 3 shows a schematic of the field and the results of the radon analysis. Concentrations ranged from 0.41 to 6.9 nCi/kg in the 12 wells along the fault and two of the three wells normal to it. One well has an abnormally high radon concentration (139 and 135 nCi/kg sampled on the two different dates) which may be due to a local radium deposit. Horne and Kruger (1979) have made a preliminary suggestion that a correlation exists between radon content and fluid enthalpy based on the hypothesis that radon emanation is strongly influenced by the density of the pore fluid. They suggest that radon concentration data across transects may provide estimates of transport following vaporization in the formation and of average formation permeability.

These early results obtained during the development of the method suggest that radon transect analysis can be valuable in determining geothermal reservoir properties. The value is amplified when analysis of stable chemical components are done in concert. Future studies should include tests in lower-temperature, liquid-dominated systems when they are available. Transect analysis should also help in the selection of wells for pressure transient and mass transient analysis, since it appears that wells in different areas of a large geothermal reservoir may be operating under different thermodynamic conditions.

Radon Emanation Studies

It is becoming increasingly evident that the "source term" of radon in geothermal reservoir transport studies is not constant under changing reservoir conditions. The emanating power of radon from formation rock is expected to be dependent on the following parameters: (1) rock type, (2) rock size distribution, (3) pore fluid density, (4) reservoir temperature, and (5) reservoir pressure. Indications of variability in emanating power have been observed in two prior experiments. The first was a set of emanation data acquired in the large SGP reservoir model using the Piledriver explosion-fractured rock loading before its use in the heat extraction experiments (Kruger and Ramey, 1977). The emanating power showed a marked gradient with temperature for gaseous pore fluid (air) but was constant with increasing temperature in liquid pore fluid (water). However, the latter data were not considered reliable because of the possibility of radon escape from the fluid in the open SGP reservoir model.

The second indication came from the results of the Phase I test in the LASL hot, dry, fractured rock reservoir at Fenton Hill, NM (Tester, et al, 1979). The radon data reported by Kruger, Semprini, and Cederberg (1979) suggested that radon emanation remained at increased levels after production ceased as long as fractures in the formation remained open under applied pressure. The radon concentration dropped to pre-test levels when the applied pressure was relieved.

During the current year, a definitive bench-scale experiment was initiated to study radon emanation under controlled reservoir temperature and pressure conditions. The model consists of three 13.5-liter steel reservoirs each loaded with 17 kg of greywacke rubble 0.6 to 1.8 cm in major dimension, in a 0.6 m^3 heavy duty oven of 340°C maximum temperature. In this model, emanation can be measured at three pressures simultaneously at each temperature. The extraction efficiency, calibrated with a NBS radium standard at standard pressure and temperature, is 60%. The radium content of the graywacke loading was determined by a standard analytical method to be 0.62±0.07 pCi/g.

Initial experiments have been run with pure nitrogen as a non-polar, non-wetting, pore fluid. Experiments with the greywacke loading have been made over a range of pressure from 15 to 300 psia and temperatures from 25 to 279°C. The data are shown in Figure 4. Two interesting observations are noted. One is the marked dependence of emanating power with pressure and temperature. The emanation is clearly a function of pore fluid density and possibly structural effects in the rock fragments. The second is the change in emanating power with temperature as the temperature was increased. The data indicates that the rock may have gone through an annealing process at the highest test temperature. Evidence for such annealing effects on radon emanation has been reported by Barretto (1975).

These experiments have suggested that emanation in geothermal reservoirs will be controlled by fully annealed formations determined by the maximum reservoir temperature. Therefore, our present experiments are being run with the greywacke loading fully heat treated at maximum oven temperature. The next set of experiments are being made with a set of increasing and decreasing temperatures to examine the extent of hysteresis in the reservoir rock annealing process.

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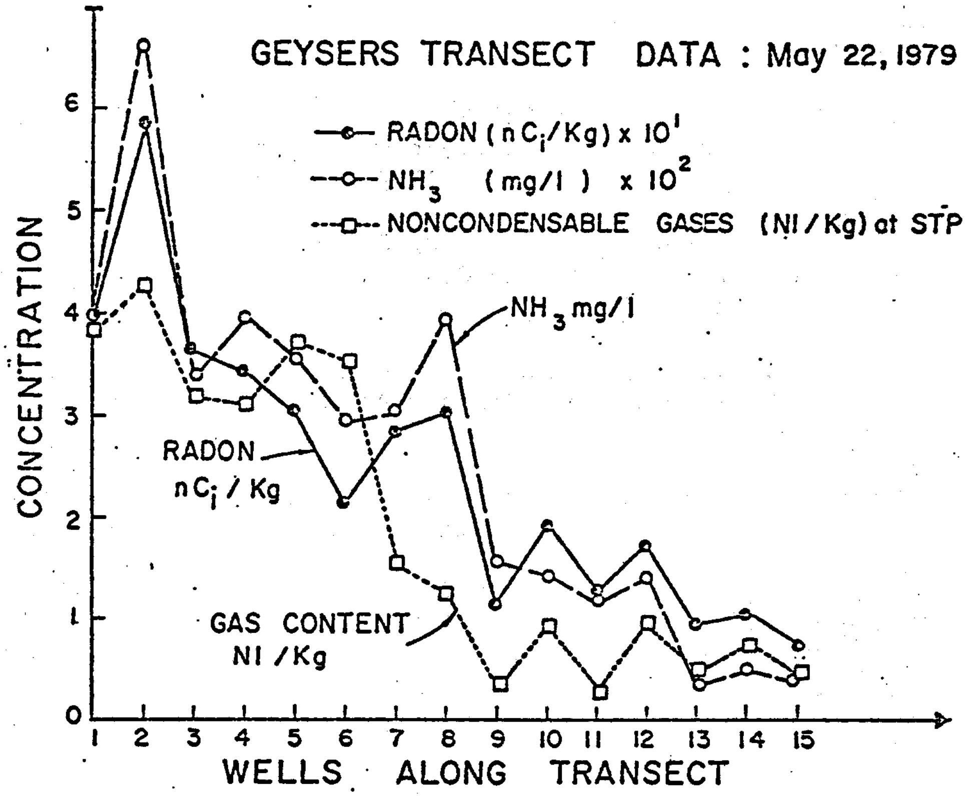

Figure 1

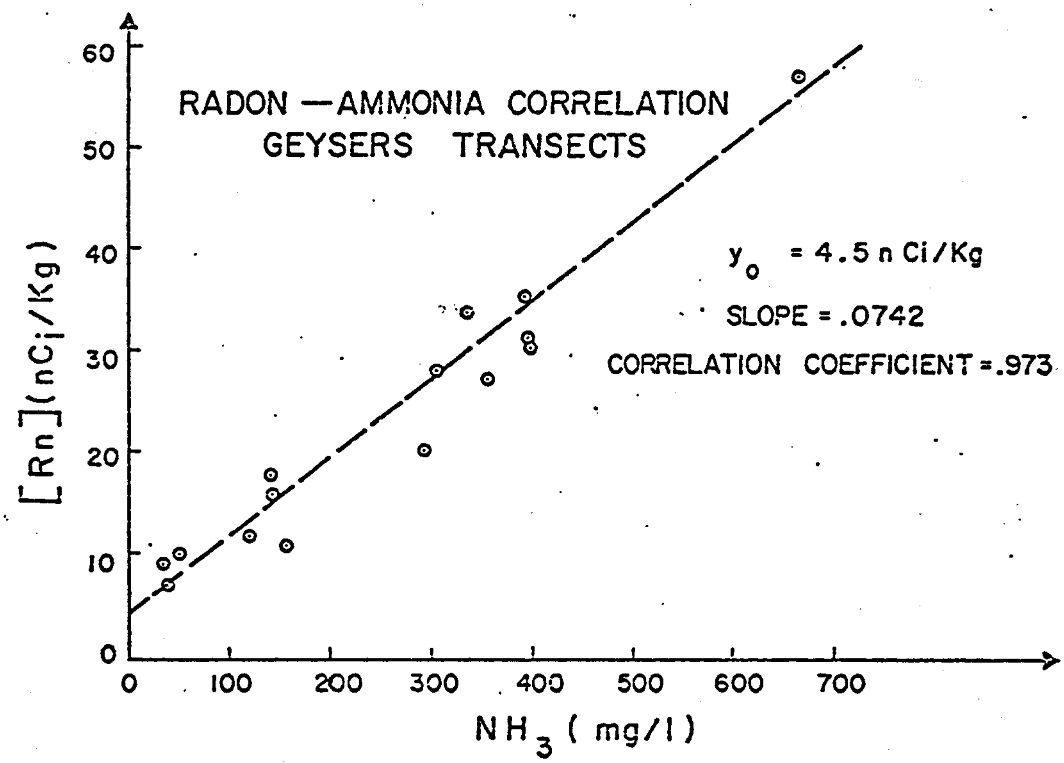

Figure 2

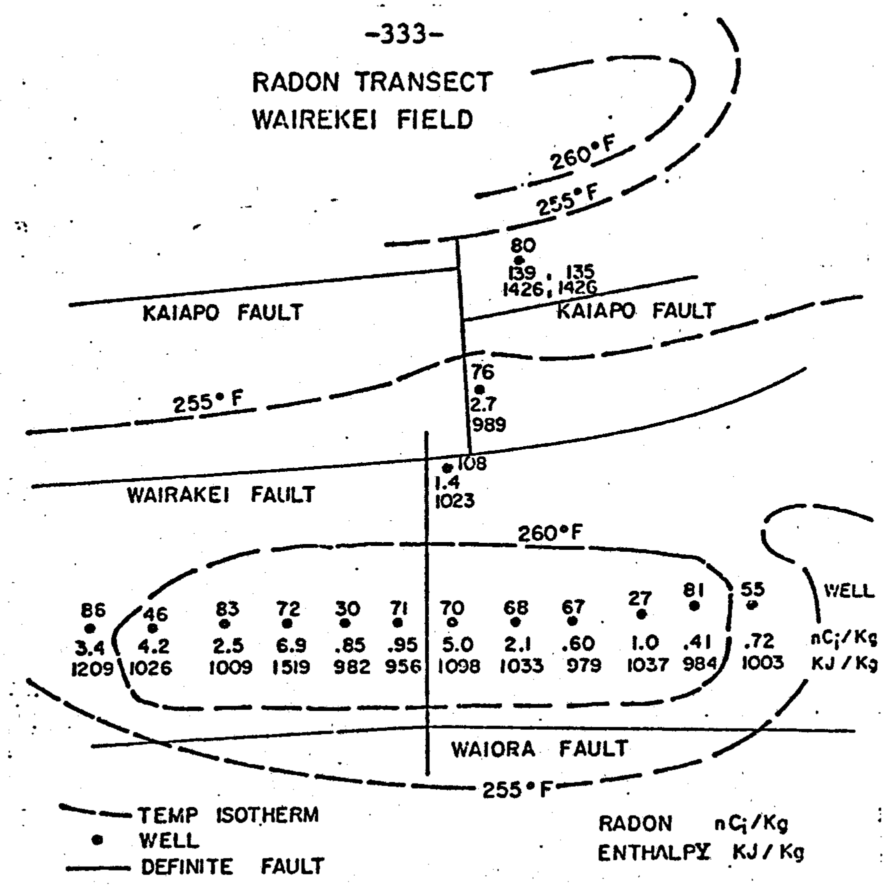

Figure 3

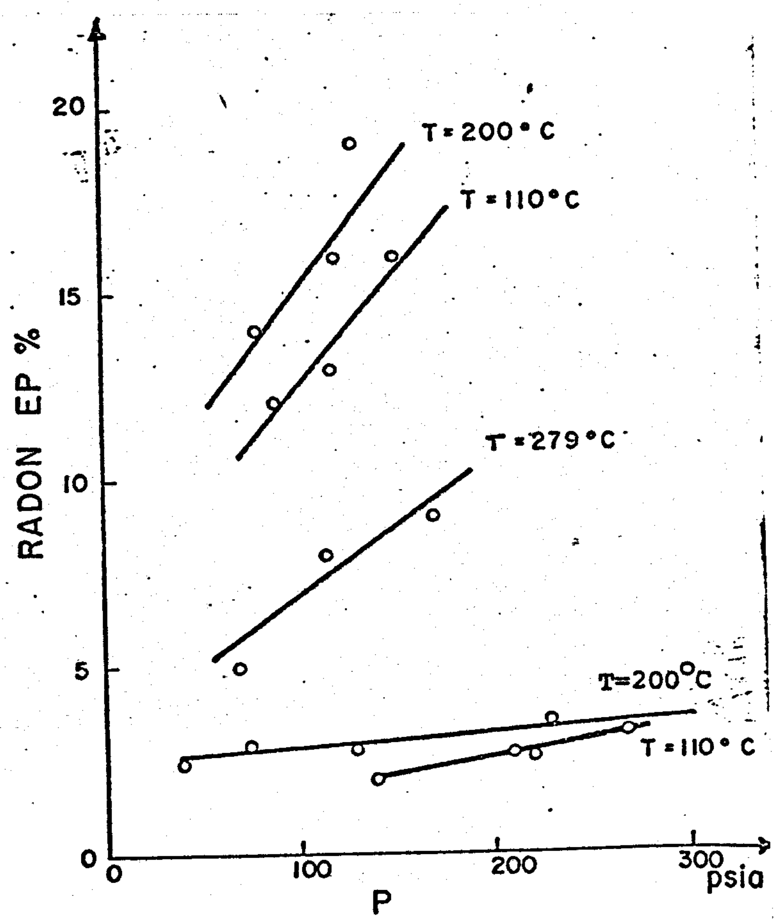

Figure 4