RADON IN GEOTHERMAL RESERVOIR ENGINEERING

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Radon is a potentially-useful internal tracer for the study of geothermal reservoirs (Stoker and Kruger, 1975; Kruger, Stoker, and Umaña, 1975). The naturally-occurring gaseous radioactive element radon exists essentially as the longest-lived isotope, 3.83-day ^{222}Rn, produced by alpha decay of 1620-year ^{226}Ra, which in turn is produced in the natural uranium series originating with 4.5×10^9-year ^{238}U. Thus radon, which decays with its characteristic half-life of 3.83 days when separated from its parent radium, will be produced "forever" from the radium found rather uniformly distributed in crustal rocks at a mean concentration of about 1 pg/g/. However, radium as a chemical homolog of the alkaline earth elements calcium, strontium, and barium, can undergo hydrothermal processes in geothermal systems and may be redistributed in a geothermal reservoir.

Stoker and Kruger (1975) noted that radon concentration in geofluids produced from active geothermal resources depends on several independent factors, among them the distribution of radium in the formation (a function of the hydro- and thermo-chemical history of the formation), the emanating power of the produced radon (a function of the physical state of the formation), and the transport time of the radon from emanation site to sampling site (a function of the hydrodynamic properties of the reservoir). Because of its relatively short half-life of 3.83-days, in contrast to the stable chemical components CO_2, H_2S, $\delta(^{18}O)$, etc., radon offers a uniquely sensitive tracer for transport time measurements in geothermal reservoirs.

Two general types of information related to transit time are amenable to radon measurement experiments. Under steady flow conditions, changes in the radon source will result in changes in the radon concentration in produced geofluids. And under steady emanation conditions, changes in the flow regime will also result in changes in the radon concentration.

Short-term changes in radon emanation can be induced by seismic activity affecting the reservoir. Such an effect seems to have occurred during experiments run for other purposes (Kruger, Stoker, and Umaña, 1975). The possibility of relating changes in radon concentration during periods of steady geofluid production with seismic events is being explored as a potential means of studying earthquakes. Short-term changes in radon emanation can also be induced by artificial fracture stimulation of low productivity hydrothermal reservoirs or of hot dry rock formations. The initial radon research program (Kruger and Ramey, 1973) was undertaken to study the possibility of determining the effectiveness of fracture stimulation methods.

Long-term changes of radon concentration in high-productivity reservoirs should be associated with long-term changes in reservoir characteristics, such as fracture density, permeability changes, lowering of boiling fronts, or redistribution of alkaline earth elements. One example of such change was noted when two wells at The Geysers sampled for radon by Stoker and Kruger (1975) were resampled two years later. The data are given in Table 1.

TABLE 1

Long-Period Sampling of Steam Wells

Well No.	Date	Flow (klb/hr)	Wellhead Pressure (psig)	Wellhead Temperature (°F)	Radon Concentration (nCi/lc)
I D	Apr '74	22.1	130	351	26.7 ± 1.0
	May '76	25.0	131	342	40.8 ± 2.8
II A	Apr '74	59.0	88	368	26.3 ± 1.0
	May '76	51.5	84	350	32.9 ± 2.2

The radon concentration (in nanocuries per liter condensate) shows a significant change over the two-year period of steady production and extensive seismic history. Although these fragmentary data are insufficient to indicate any of the long-term changes in reservoir characteristics noted above, they do indicate a reasonable justification for long-term measurement of radon emanations in several wells over the reservoir.

Current interest has focused on the relationship between radon concentration and the flow regime in producing geothermal reservoirs. Steady-state production should result in a steady-state concentration of radon gas on the basis of a constant emanation rate of radon from the reservoir rock, a constant permeability field in the reservoir, and thus a constant transport time from the emanation or boiling site to the wellhead.

Several indications of a dependence of radon concentration on flow rate in producing geothermal reservoirs have been observed. The basis for flow models in vapor-dominated and liquid-dominated reservoirs was given by Stoker and Kruger (1975). For a one-dimensional linear vertical model of a steam reservoir, in which the radon is boiled out with the steam from a deep liquid zone, and little radon emanates into the dry steam zone below the well, the concentration should be directly related to the flow rate, for which the transit time is a function of the permeability-distance product, Kh. A model of such flow is given in Muscat (1946) as the "open-bottom" well, a three-dimensional reservoir of great thickness. Figure 1 shows the first test of radon concentration dependence on flow rate at The Geysers well (Kruger, Stoker, and Umaña, 1975). The transient, following a flow rate shut-in from ∿100 Mt/hr to ∿50 Mt/hr, shows a period of about 21 days in change of concentration from an average of 16.5 $\pm$ 2 to a test termination value of ∿8 $\pm$ 1 n Ci/lc.

Several attempts have been made to reproduce this observed linear change in concentration with flow rate. Samples taken weekly at another well at The Geysers this summer in preparation for a double draw down test showed a qualitative dependence during a period of shut-in unknown to us. Figure 2 shows the data during this period. Completed analysis of 19 samples obtained during the period 1 to 2 months prior to the shut-in showed a mean concentration of 18.4 ± 0.4 nCi/lc at a steady flow rate of 130 klb/hr. The random samples taken after the then unknown shut-in period showed a curious pattern. The first sample taken 15 days after the initial shut-in showed a significant decrease; the second sample, showing a major decrease, was taken 18 and 11 days respectively after the second and final flow rate changes. The third sample was taken 15 days after the return to full flow and the fourth sample was taken one day later. The similarity in patterns between flow rate and radon concentration with an apparent 15-16 day phase lag is qualitatively striking.

Current experiments include a full 24 day, double flow rate shut-in at The Geysers with samples taken daily at this and a nearby monitoring well without change in flow rate. A two-week half-flow shut-in test is scheduled for a well in the Larderello steam fields for November, 1976. The results of these experiments is expected to assist in the formation of a quantitative model of radon flow in steam reservoirs.

Other experiments are underway to obtain steady flow rate radon concentrations in liquid-dominated reservoirs in anticipation of flow rate change experiments when sufficient periods of production are available and reduction in flow does not interfere with production operations. Tests are underway at Well 6-1 of the East Mesa facility operated by the Bureau of Reclamation, at Cerro Prieto through the courtesy of the Comision Federal de Electricidad and at Heber in conjunction with a long-term heat exchange test supported by the Electric Power Research Institute. A model for radon concentration change with flow rate change was suggested by Stoker and Kruger (1975) as the horizontal flow confined aquifer, in which the concentration would be dependent on the logarithm of 1/Q rather than directly proportional to Q itself. Verification of this model requires substantial sampling under steady operating conditions to obtain a sufficiently small standard deviation in the mean concentration of radon which should vary logarithmically with flow. The results of these tests will be given in subsequent reports.

References

Kruger, P. and H. J. Ramey, Stimulation of Geothermal Aquifers, Progress Report No. 1 to National Science Foundation, SGP-TR-5, March, 1973.

Stoker, A. K. and P. Kruger, Radon in Geothermal Reservoirs, Proc., Second UN Symposium on the Development and Use of Geothermal Resources, San Francisco, May, 1975.

Kruger, P., A. K. Stoker, and A. Umaña, Radon in Geothermal Reservoir Engineering, Proc., Application of Nuclear Techniques to Geothermal Studies (International Atomic Energy Agency, Vienna, 1975) in press.

Muscat, M., The Flow of Homogeneous Fluids through Porous Media (Edwards, Ann Arbor, 1946).

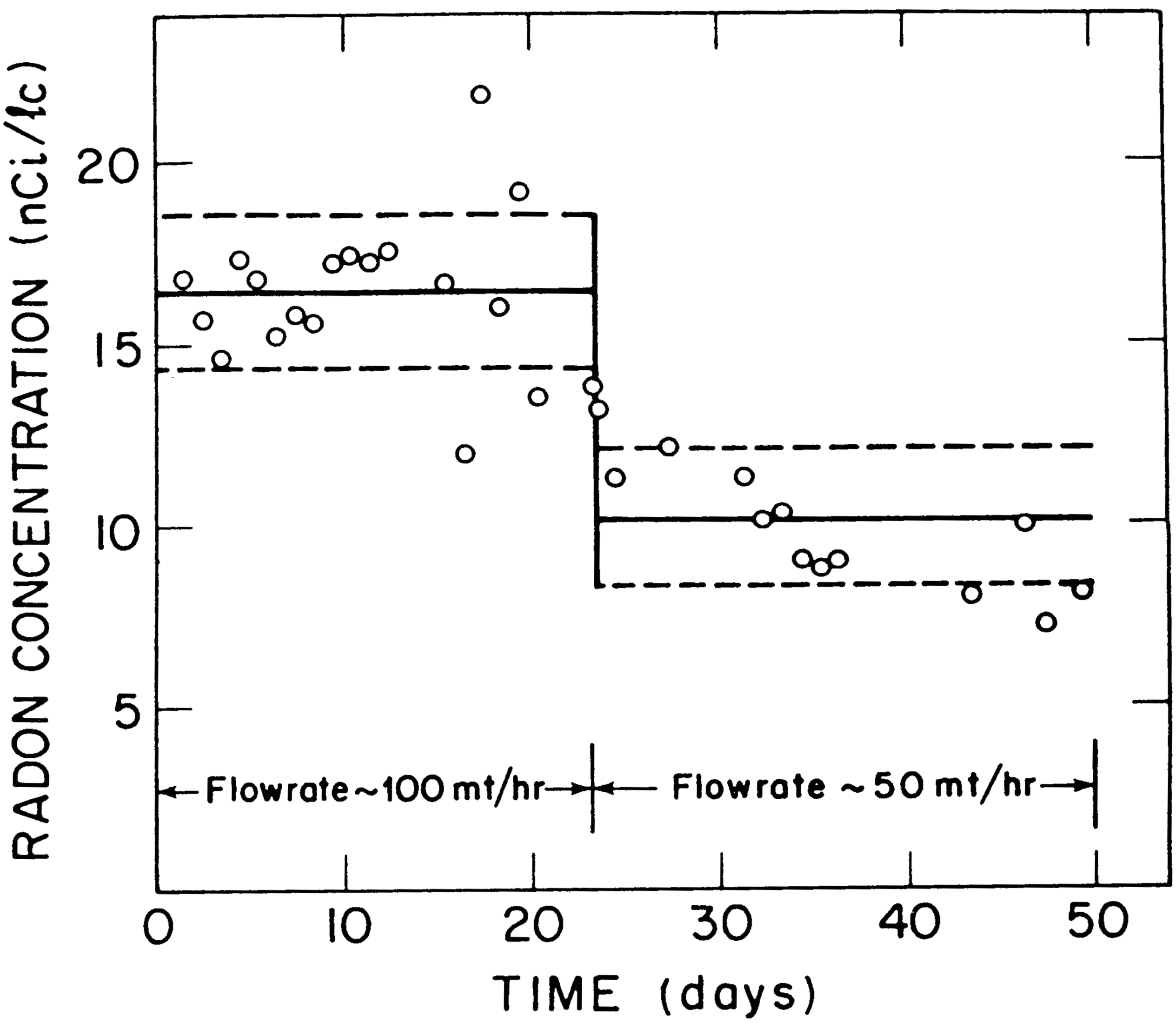

Figure 1. Radon concentration during a flow rate change. Solid lines are mean values over the flow rate period; broken lines represent one standard deviation.

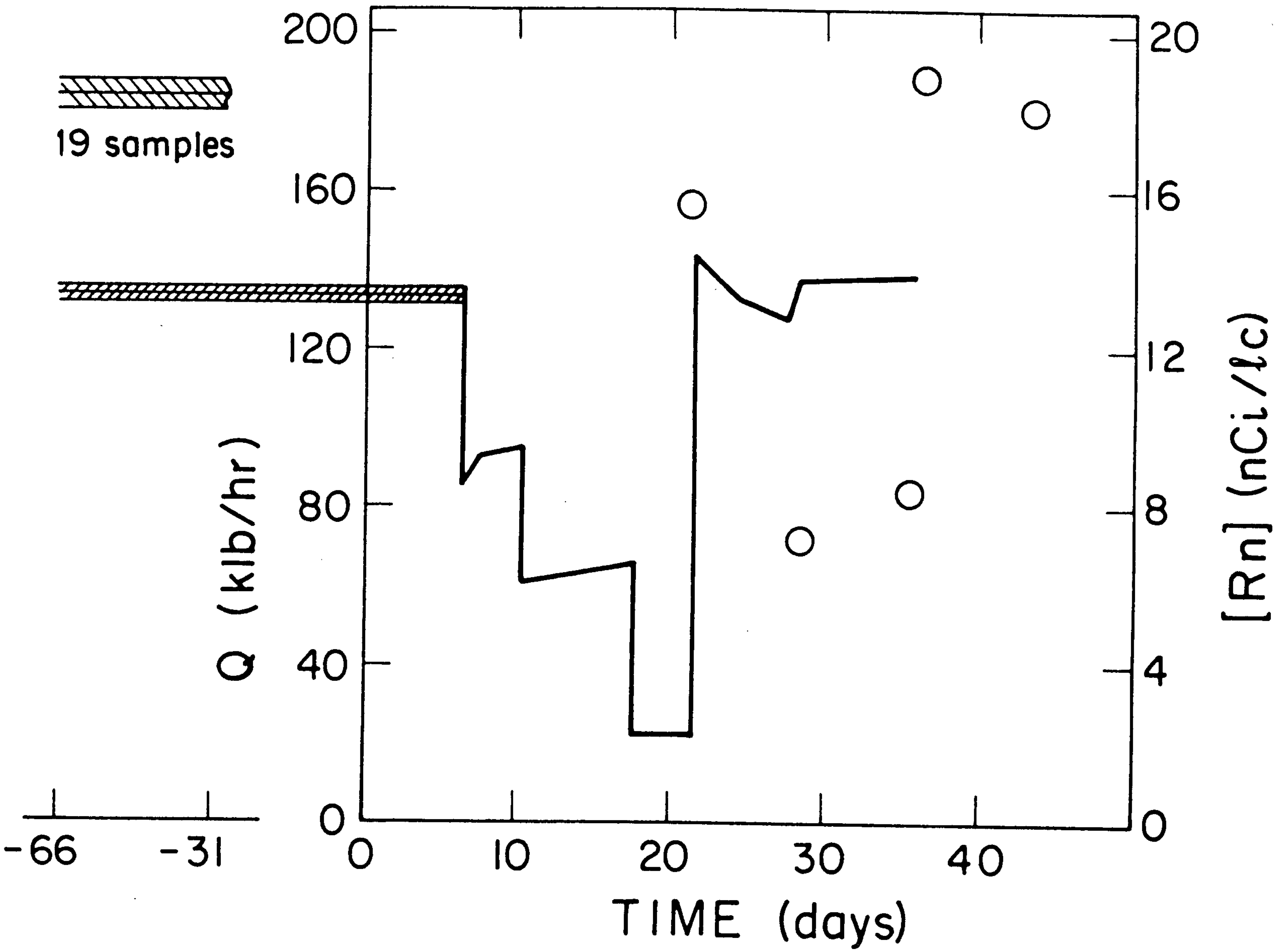

Figure 2. Radon concentrations during a period of changes in steam flow rate