RECENT RADON TRANSIENT EXPERIMENTS

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Radon transient analysis is being developed as a method complementary to pressure transient analysis for evaluation of geothermal reservoirs. The method is based on the observations of Stoker and Kruger (1975) that radon concentration in produced geothermal fluids is related to geothermal reservoir type, production flow rates, and time. Stoker and Kruger showed that radon concentrations were markedly different in vapor-dominated and liquid-dominated systems, and varied not only among wells of different flow rate in an individual reservoir, but also varied timewise in individual wells. The potential uses of radon as an internal tracer for geothermal reservoir engineering were reviewed by Kruger, Stoker, and Umaña (1977). **Also** included were results of the first transient test performed with rapid flow rate change in a vapor-dominated field. The results of the next four radon-flow rate transient experiments were summarized by Kruger (1978) in which effects of well interference and startup production in a new well were demonstrated. Four of these first five radon transient experiments have been carried out in vapor-dominated reservoirs at The Geysers in California and Serrazzano in Italy. The systematics of the transients of radon concentration following abrupt changes in flow rate is being evaluated by Warren and Kruger (1978). The fifth test was at the HGP-A well in Hawaii, the first transient test in a liquid-dominated reservoir.

Three additional radon transient tests have been carried out, each in a different type of geothermal resource. The first test was in a petrothermal resource, the reservoir created by hydraulic fracturing by LASL in the hot, dry rock experiment in New Mexico. The results of this first 75-day production test of continuous forced circulation, during January-April, 1978, are given by Tester, et al (1978). The results of the radon concentration measurements made during this test are summarized by Kruger, Cederberg, and Semprini (1978). The second test was a second transient test at the HGP-A well in the liquid-dominated reservoir at Pohoiki, Hawaii, and the third test was a second transient test at the Grottitana well in the Serrazzano field at Larderello, Italy. The general observations of these tests are listed in Table 1. A summary of each of these three tests follows.

During the LASL hot dry rock flow test, five samples of re-circulating production fluid were obtained by wellhead sampling. Two samples were obtained during the following shutin and venting periods *of* the test, and one sample of makeup water was analyzed during the test. The radon concentration data are given in Figure 1. The data show a qnasi-exponential growth in radon coccectration

TABLE 1

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Site	Date	Test Conditions	Observations
LASL Hot, Dry Rock Fenton Hill, New Mexico	Spring, 1978	Recirculated water as forced circulation through hydraulic cracks	Logistics Growth of [Rn]
Univ. Hawaii HGP-A Pohoiki, Hawaii	(1) July, 1977 (2) July, 1978	Short period (~4 hr) flow tests through two orifice sizes	(1) [Rn] constant with flow rate (2) [Rn]/Q growth with production?
ENEL Grottitana Serrazzano Italy	(1) Nov-Dec, 1976 (2) Aug-Sep, 1978	Long period (3 week) flow tests with two rapid changes in flow rate, *Q*	(1) [Rn]/Q constant (2) $[Rn]/Q = F(Q_{th})$?

during the 75-day test period. The first sample, collected 6 hours after initiation of the flow test period, was water resident in the large fracture volume during the prior 3-month shutin period and should represent geofluid radon in equilibrium with radon emanation from the fractured rock. The second sample indicated a dilution of this concentration with the large amount of makeup water required during the first 20 days of flow. The rise in concentration during the remainder of the test can be described by exponential growth of the form

$$[Rn] = [Rn]_o \; e^{+kt}$$

where k *is* a growth constant with the value 0.035 ± 0.005 for the first four samples. The fifth sample showed a value of $k = 0.071$ indicating a trend toward a logistics growth of the form shown in Figure 2 by

$$[Rn] = \frac{[Rn]^{\infty}}{1 + ae^{-bt}}$$

where $[Rn]^{\infty}$ is the infinite-time steady-state radon concentration for finite radium concentration and constant emanation and thermodynamic conditions; and a and b are empirical constants estimated by least-square fit as given in Figure 2. The value of $[Rn]^{\infty} = 11.2$ nCi/l is based on the LASL measurement of $[Ra] = 1.7$ pCi/g in core rock and assumed values of emanating power, rock porosity and density, and the volumetric estimates of the fracture volume and total circulation volume. Four mechanisms for the observed quasi-exponential growth in radon concentration have been evaluated.

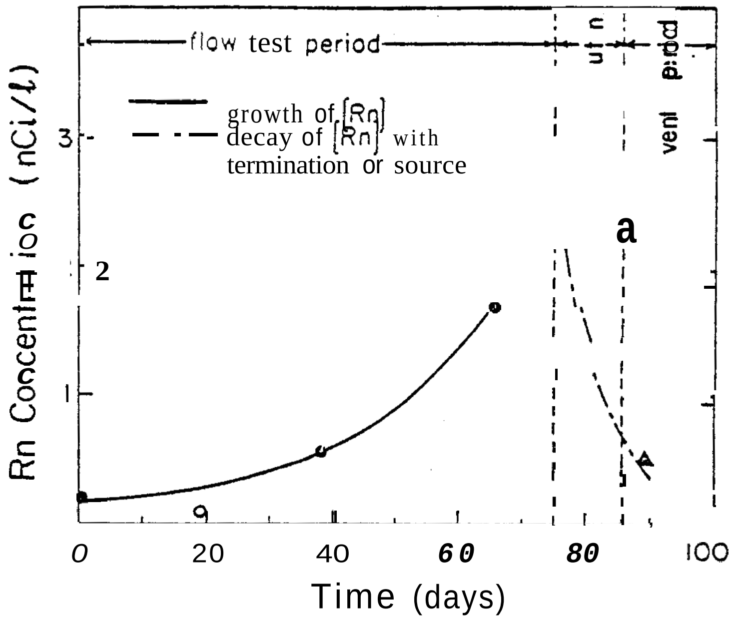

Figure 1. Radon data from the LASL Phase I test

Two of these, (1) the possibility of continuous radium dissolution and (2) the increase 'of radon solubility with decreasing reservoir temperature, have been discarded. The two remaining mechanisms, (3) an increase in emanating power of radon by recoil or diffusion from the rock to the recirculating fluid, or (4) an increase in the area of fractured rock surface (at constant emanating power) through increased fracturing of the formation by the recirculating fluid pressure and temperature differential cannot be distinguished. Current investigations by Macias (private communication) to determine the dependence on radon emanation on the pressure, temperature, and pore fluid density in fractured rock should assist in examining these two mechanisms.

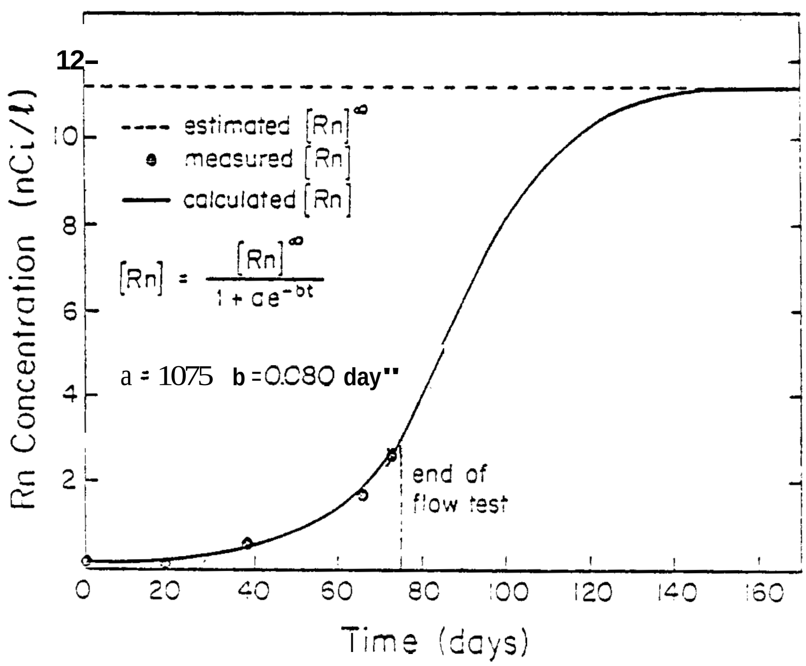

Figure 2. Logistics curve for Phase I radon data

The second test at the HGP-A well in Hawaii was run in July, 1978 in a manner similar to the first test of July, 1977 described by Kruger (1978). Both tests, with flow duration limited by environmental constraints, were run with changes in orifice plates to provide maximum flow through an 8" hole and minimum flow through a 1-3/4 - 2" hole. Flow rates were measured by the Russell James lip-flow pressure method (1962). The radon concentration and flow rate data are shown in Figure 3. Both short-period tests show essentially a constant radon concentration, independent of flow rate, in accordance with the horizontal flow model proposed by Stoker and Kruger (1975). However, the short flow periods preclude observation of any longer period transient. Several interesting trends are noted in the mean value data given in Table 2, primarily the increase in radon concentration per unit flow rate resulting from both an increase in mean radon concentration and a decrease in flow rate between the two tests. This observation may be consistent with the growth in radon concentration noted by Warren and Kruger (1978) for a newly producing well in a non-producing section of The Geysers geothermal field. If the model of "boil out" of condensed fluid near the wellbore is valid, observation of increased radon concentration per unit flow rate with further production in the HGP-A well can be predicted.

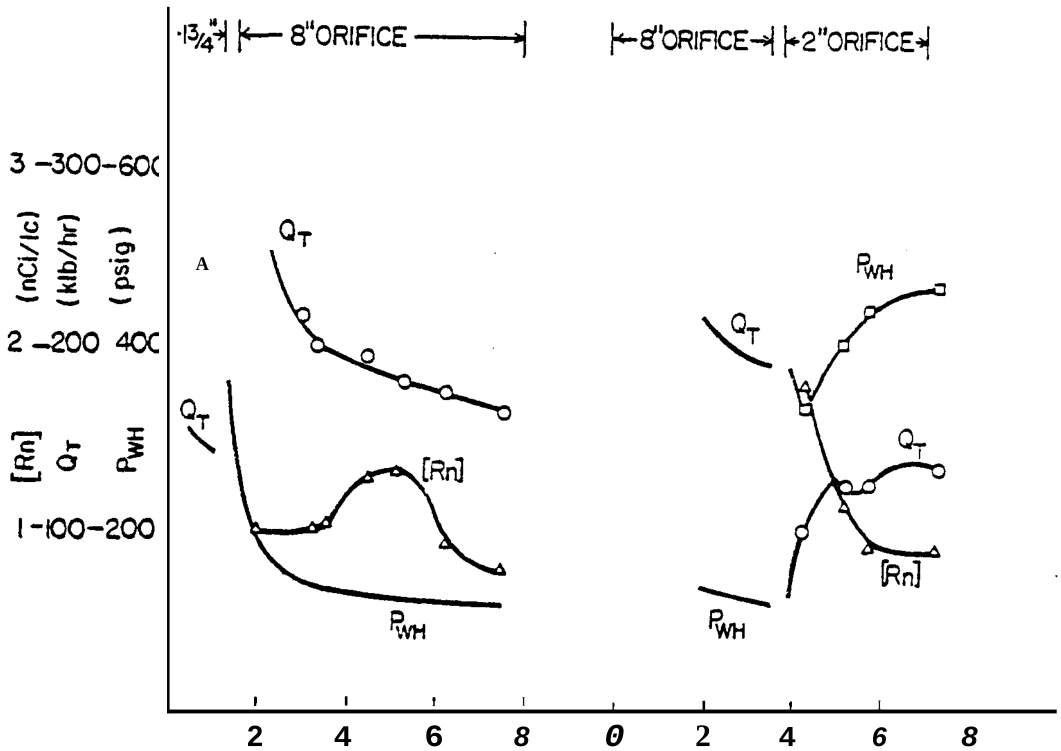

Figure 3. Radon data from HGP-A well in Hawaii, 1973

The second test at the Grottitana well at Serrazzano, Italy was run in August 1978 in cooperation with the ENEL staff in Castelnuovo. The preliminary results of this test, shown in Figure 4, agree well with the results of the November 1976 test, again showing a strong dependence of radon concentration on flow rate. However, Table 3 shows an interesting difference in this dependence related to the range of flow rates obtained. In the initial test, the flow rate was decreased from the full normal of about 11.8 t/hr to a value of about 7.5 t/hr. The observed transient was rapid (less than 1 day) and the radon concentration per unit flow rate was constant at a value of 7.33±0.76 over the entire flow rate range. In the current test, the flow rate was reduced in two stages, from 11.3 t/hr to 8.1 t/hr and then to about 5 t/hr. The two samples obtained for the first reduced flow rate showed a [Rn]/Q value in agreement with the previous value for the same flow rate change, but differed markedly for the lowest flow rate. Three possible physical reasons could account for this non-linear dependence on the lowest flow rate: (1) the increased reservoir pressures associated with the lowest flow rate sufficient to result in increased emanation from the reservoir rock (as indicated in the **LASL** hot dry rock experiment); (2) the possibility of a non-linear contribution from radon emanated from the boiling front to the well, as suggested for steam systems by Warren and Kruger (1978); and (3) the possibility of partial condensation of the steam under subcooled conditions during transit to the well. Here again the experimental data of Macias on emanation under known reservoir conditions will **be** of value in distinguishing between these possibilities.

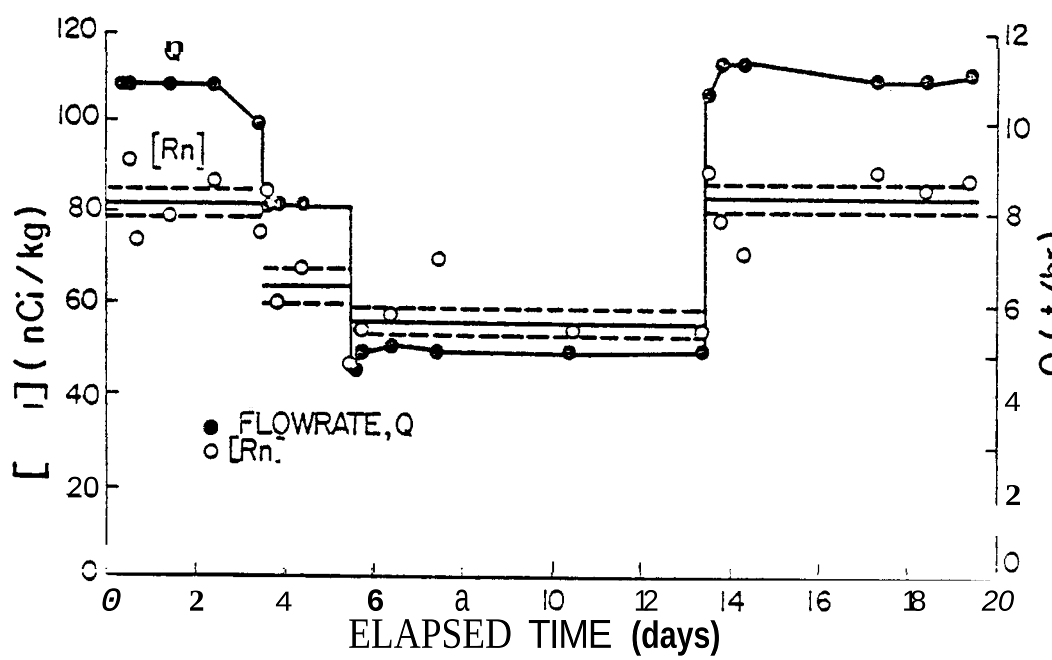

Figure 4. Radon data from Grottitana well, Italy

TABLE 2

RADON TRANSIENT TESTS - POHOIKI, HAWAII

Date	Orifice (inches)	$\bar{Q}$ (klb/hr)	[$\bar{Rn}$] (nCi/kg)	[$\bar{Rn}$]/Q $\left(\frac{pCi/kg}{mt/hr}\right)$
July, 1977	8	236	0.89	1.41
	1-3/4	137	0.85	2.82
July, 1978	8	201	1.22	2.76
	2	121	1.20	4.50

TABLE 3

RADON TRANSIENT TESTS - GROTTITANA, ITALY

Test Dates	[Rn]/Q Ratio	Q Range (t/hr)
Nov - Dec 1976	7.33 ± 0.76	7.5 - 11.8
Aug - Sep 1978	7.8 ± 0.3	8.1 - 11.3
	11.5 ± 0.6	4.6 - 5.0

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