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# RADON MEASUREMENTS IN GEOTHERMAL SYSTEMS

by

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# ABSTRACT

Radon is a naturally occurring radioactive gas produced by the decay of radium. Its presence in geofluids has been observed in hot springs and water, oil and natural gas wells. This study is concerned with radon in geothermal reservoirs.

Radon release from geothermal reservoirs depends on the concentration and distribution of radium, the emanation properties of the radon, and the flow characteristics in the reservoir. At steady state, the radon concentration in produced geofluids is a function of the volumetric emanating power and the effective porosity. Thus, radon may serve as a subsurface tracer in geothermal reservoir engineering for evaluating the effectiveness of stimulation techniques which change the values of these parameters. Because of its radioactivity, radon release is also of environmental concern. Several sampling and measurement techniques were evaluated to provide representative values of radon concentration for engineering and environmental studies. Results showed that radon concentration in geofluids from several geothermal reservoirs varied significantly with time. At production rates, the Concentration of radon relative to both the condensate and the carbon dioxide component of the non-ccnlensable gases varied not only between wells in a given field but also within a single well. Data at several flow rates indicated a possible dependence of effective emanating power on formation pressure. The effect of changing flow rate on radon concentration may be predicted by theory. Tests during drawdown calibrations indicated an approach to steady-state concentration, perhaps independent of flow rate. The environmental impact of radon release to the atmosphere appears to be small and indistinguishable from the release of radon by natural emanation from the surrounding land mass.

# ACKNOWLEDGEMENTS

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# CHAPTER 1

# INTRODUCTION

The development of geothermal energy resources may result in the extraction of commercial quantities of the vast thermal energy reserves stored in earth's crust. The U.S. Department of the Interior (1973) indicates that geothermal energy may contribute between 0.2 and 8 per cent of **U.S.** electric generating capacity by 1985, and between *1.5* and 14.4 percent in the year 2000.

Major technical problems require solution if these estimates are to be translated into reality. One of these is the need to understand the geologic processes which govern the subsurface flow of heat-carrying fluids essential for extracting geothermal energy. Radon, **a** radioactive gas continuously produced in small quantities in natural rock and transported by geofluids, may serve as a tracer for studying such subsurface processes.

A second major consideration is the mandate under the National, Environmental Policy Act of 1969 (NEPA) for comprehensive evaluation of environmental consequences of technological innovations. While geothermal heat is generally considered to be a relatively clean source of energy, **a** potential for release of geofluid contaminants to the environment does exist. Under the provisions of NEPA, these potential environmental impacts will require evaluation of the magnitude and importance and controls when detrimental effects are found. Scott (1972) has suggested that the release of radon from extracted geothermal fluids may constitute an environmental impact which should be examined.

Thus, this study examines the role of radon in geothermal systems from two major perspectives: (1) its possible use as a natural tracer for studying subsurface geofluid flow phenomena, and (2) its possible significance on release to the environment from geothermal reservoirs.

## Basic Characteristics of Geothermal Resources

An exploitable geothermal reservoir is generally considered to consist four major elements: (1) a concentrated source of heat, such as a magma chamber, relatively near the surface, (2) a porous or fractured rock formation, (3) an adequate supply or renewable source of fluid to extract the thermal energy, and (4) an impermeable capping formation to confine the fluids and energy in the reservoir. All currently exploited geothermal resources have these four components naturally present. Many proposals for stimulating the production of geothermal energy have been suggested. These generally involve the creation of an artificial circulation system for heat extraction.

Geothermal resources may be divided into four general classes: (1) vapor-dominated, (2) liquid-dominated, (3) geopressured, and (4) hot dry rock, based on their natural geologic characteristics. Vapor-dominated and liquid-dominated systems are considered variants of hydrothermal-convection systems by White, et al. (1971) and White (1973).

Geothermal energy production is currently limited to the expoitation of such hydrothermal-convection systems. Hydrothermal-convective systems tend to occur in geologic zones of tectonic, volcanic, or orogenic activity and contain natural fluids which circulate and transfer heat. Convection results when fluids heated at the base of a system expand and rise due to buoyant forces. The heated fluid may appear at the surface in the form of hot springs, geysers, or fumaroles, or may return to depth after transferring some of its heat to rocks nearer the surface.

The essential difference between vapor-dominated and liquid-dominated systems is the physical state of the pressure-controlling phase (White, 1973). Liquid- or water-dominated systems have liquid water as the continuous phase. Pockets or bubbles of vapor may exist, particularly at shallow depths. White describes many variations, depending on geologic structure, temperature, and chemical constituents in the liquid. Major systems of this type include those at Wairakai, New Zealand; Otaka, Japan; Cerro Prieto, Mexico; and the Imperial Valley in southern California.

Vapor-dominated systems have steam as the predominant continuous phase. Liquid water is likely to be present at depth to replenish the steam lost from the reservoir. It is also possible that vapor-dominated systems may develop from hot-water systems in which recharge rates are too low to replenish the fluid boiled off (White, 1973). Although most geothermal power plants are located at vapor-dominated reservoirs, such as Larderello, Italy; Matsukawa, Japan; and The Geysers area of California, Barnea (1972) has suggested that liquid-dominated systems are 20 times more common.

Geopressured reservoirs occur in deep sedimentary basins found around the Gulf Coast of the U.S. and in parts of eastern Europe. Their elevated temperatures evidently result from the insulating effect of clay layers. Temperatures of 290°C and pressures of 500 atmospheres have been measured (U.S. Dept. of the Interior, 1973). Thus the possibility of extracting mechanical energy as well as thermal energy from such reservoirs exist. Schmidt (personal communication) notes that geopressured water may range from nearly pure to heavy brine, and dissolved methane may also be present.

Hot dry rock geothermal systems occur in many places but are still further from economic exploitation. They lack at least one or two of the essential components of a reservoir: the fluid and the fractured or porous media. These systems will be useable only with successful development of the technology for creating porosity and permeability and introducing a system of fluid circulation.

## Production Modis, Performance Prediction

Utilization of geothermal energy may occur in several ways. Although the major present and projected purpose is electrical power generation, other applications are promising. Geothermal energy can be used directly for heating and airconditioning of buildings, applications in agronomy such as hothouses, and process-heating in manufacturing. The mineral content of some hot-water systems may be economically recoverable. Desalination of hot brines may add significant amounts to fresh-water supplies in some areas (Muffler, 1973).

The method of producing geothermal fluids depends on the nature of the resource and the application. The major methods presently include direct production of steam from vapor-dominated reservoirs and flashing of hot water from liquid-dominated reservoirs.

Electric power production generally depends on the direct utilization of saturated or superheated steam to drive the turbine-generators. At The Geysers power plants, wells of 180 to 2750 meter depth yield steam at rates of 5 to 38 kg/sec which is delivered to the turbines at about 100 psig and 350°F. About 0.0025 kg/sec of steam is required for each kilowatt of generating capacity. An efficiency of about 14 per cent is realized. After condensation, approximately 80 per cent of the mass flow is lost to the atmosphere by evaporation in cooling towers; the other 20 per cent is injected into the reservoir formation (Budd, 1973; Finney, 1973).

Present techniques of power production based on hot-water systems depend on flashing part of the liquid into steam as pressure is reduced. At Wairakei and Cerro Prieto, for example, about 20 per cent of the mass flow flashes and the resulting steam is fed to low-pressure turbines, similar in specifications to those used at The Geysers. Because of the heat contained in the separated liquid fraction, thermal efficiencies are only on the order of 8 per cent (Muffler, 1973), and the required mass rates are typically 5 to 8 times those of vapor-dominated production.

Alternate energy extraction technologies are being investigated to improve conversion efficiencies and implement utilization of lower-temperature and highly-mineralized water. Among the promising possibilities is the binary fluid cycle in which geothermal water is maintained under pressure through a heat exchanger and then injected into the formation (Anderson, 1973). A second process involves the use of an impuse turbine which may be able to utilize the mechanical as well as the thermal energy of the total mass flow (Austin, et al., 1973). Another concept depends on controlling the flashing process within the reservoir formation (Ramey, et al., 1973). This non-isothermal process would permit recovery of energy from the formation rock as well as the liquid and result in a greater extraction efficiency of the energy stored in the reservoir.

## Stimulation Concepts

Stimulation of geothermal energy production includes methods for increasing both the conversion and extraction efficiences. Stimulation can be achieved by improving the performance of natural reservoirs or by the creation of useable reservoirs in otherwise unexploitable geothermal resources (Ewing, 1973). Among the techniques that have been proposed are hydraulic fracturing, thermal stress cracking (Smith, et al., 1973), chemical explosive fracturing (Austin and Leonard, 1973), and nuclear explosive fracturing applied to natural aquifers (Ramey, et al., 1973) or hot dry rock (e.g. Burnham and Stewart, 1973).

The major effects of fracturing or cracking stimulation include increased porosity or void space and increased permeability. The functional results for increased geofluid production include greater fluid flow by reduced resistance to flow, and in-situ flashing in the enlarged void spaces.

## Geothermal Resource Evaluation and Testing

Improved methods are needed for locating, drilling, and production testing of geothermal reservoirs. Geologic structure and surface features, including hydrologic manifestations such as hot springs, are often preliminary prospecting indicators. Geophysical techniques, such as temperature gradient surveys, heat flow determinations, electrical methods, 2nd seismic activity measurements, are frequently used. Geochemical methods are also useful in evaluating potential geothermal resources. For example, chloride content can be used to distinguish between hot-water and vapor-dominated systems. Other dissolved constitutents, notably $SiO_2$ and Na-K-Ca relations are also used as geothermometers (Combs and Muffler, 1973). Ratios of oxygen and hydrogen isotopes may lead to identification of the source of the water in a reservoir.

Production performance testing of individual wells and entire reservoirs is a crucial step in the development of a geothermal resource. Major economic decisions regarding the capitalization of generating plants must be made on the basis of predicted performance. For reservoirs produced under essentially isothermal conditions, i.e. all-liquid or all-vapor, analytic methods generally employed in hydrology, petroleum, and natural gas reservoir engineering may often be applied (Ramey, 1970). When two-phase fluids coexist in the reservoir, a more specific model involving both mass and energy balances is essential (Whiting and Ramey, 1969). Performance matching models involving observations of production conditions at the wellhead, together with available information on volumetric and flow properties of the reservoirareused to define the resource in a quantitative way such that long range predictions can be made.

For evaluation of potential stimulation methods, it would be particularly useful if additional diagnostic tools could be made available to determnne the anticipated effects produced in the reservoir.

## Environmental Aspects

Geothermal energy is generally regarded as being a relatively non-polluting form of energy production. Since this regard might be due simply to its present low level of public visibility, a general perspective of potential impact is necessary as some environmental inferences will be discussed later in this work.

The major impacts of geothermal energy development may include effluents discharged to surface or groundwater, atmospheric emissions, noise, visual impact, land subsidence, induction of seismic activity, modification of land use patterns, and direct damage to ecologic communities resulting from the industrialization (U.S. Dept. of the Interior, 1974). The magnitude and importance of each effect will depend on the particular resource, the mode of power production, and the level of development.

The potential effects must be weighed against both absolute criteria, such as air and water quality standards, and relative criteria, such as the comparative effects of generating the same power by alternate technologies. For example, disposal of liquid effluents by injection is contemplated for most sites because the discharges will generally exceed standards for dissolved constituents insurface waters. The problems are generally much less severe, though not vanishingly so, for steam reservoir situations compared to hot-liquid systems because of the much lower liquid production rate and the frequently lower mineral content.

In contrast with alternate technology, geothermal effluents may differ in both composition and quantity. Non-condensable gases released from a geothermal plant may contain hydrogen sulfide, ammonia, and methane. The sulfur content of the $H_2S$ will be generally less than the sulfur as $SO_2$ emitted from a coal burning plant of the same capacity. On the other hand, a geothermal plant does not release other significant air pollutants typical of a coal plant, i.e., nitrogen oxides, carbon monoxide, and flyash particulates. Some geothermal cycles can produce their own cooling water; but all geothermal electric power stations have to reject 4 to 6 times as much waste heat as conventional fossil- or nuclear-fueled plants because lower natural steam temperatures limit thermal efficiency (Hughes, 1973). Geothermal plants occupy a fairly large land area with their network of wells and gathering lines--about 1 square mile for each 100 megawatts of capacity. But, there are no operations which leave the landscape deeply scarred and mine tailings or overburden piles often required for coal and uranium extraction.

In short, the problem of environmental impact is complex; no simplistic comparisons can be made of the tradeoffs and intermedia exchanges. However, even though some problem areas will require adequate control, geothermal energy production apparently has distinct advantages in many areas of environmental concern.

## Radon in Relation to Geothermal Resources

The discussion of geothermal resources introduces the interest in radon and defines the broad goals of this study from the two perspectives noted at the outset.

Radon is a radioactive noble gas, with a half-life of 3.8 days. It is produced continuously in all geofluids by radioactive decay of radium with a 1602-year half-life. Radium is present in most rock at concentrations of about 1 pg/g depending on the extent of equilibrium with its precurser members of the natural uranium series.

The extent of radon release, or emanation, is dependent on several factors including the distribution of radium through the rock matrix and the surface area available for escape of recoiling radon atoms. The concentration of radon in geofluids reaching the surface depends on the emanation as well as the volumetric properties of the porous or fractured media and the flow conditions of the transporting fluids. In particular, the flowrate determines the time available for accumulation or decay of radon in a unit volume of fluid before it reaches the surface through a well or natural fissure.

<u>Possibilities for Radon as a Subsurface Tracer</u>--Because the amount of radon present in geofluids is dependent on both the geologic properties of the formation media and the flow-determined temporal history of the fluid passing through the media, observations of the radon content of a produced fluid may be useful for studying subsurface conditions.

Radon occurrence has been studied with respect to groundwater flow, natural gas production, and uranium prospecting (e.g. Tanner, *1964;* Bunce and Sattler, 1966; Tokarev and Shcherbalcov, 1960). In hydrology it has been used to trace fluid origins. Radon and radium have long been associated with hot springs; and radon has been observed in conjunction with some geothermal phenomena (Belin, 1959). Radon was also measured in the Rulison natural gas stimulation experiment (Kruger, 1974).

Accordingly, the work described in this project was initiated as a feasibility study of the use of radon as a diagnostic tracer in geothermal resource development. The basic goal is an assessment of the potential of radon as a tracer, especially in relation to possible application as an indicator of stimulation effects in rock media.

Possible Environmental Considerations--The properties of radon that make it interesting as a tracer, namely its radioactivity and its transport to the surface in geofluids, lead to the need to consider potential environmental implications of its release to the environment resulting from geothermal energy production. The Environmental Protection Agency has raised the question of radon environmental effects (Scott, 1972), and the Department of the Interior will require measurement of radon at each federal geothermal lease site (Dept. of the Interior, 1974). Published measurements of radon in geothermal fluids used for energy production are not generally available. Only speculative estimates of the possible significance of radon release resulting from geothermal energy extraction have been made. Therefore a secondary objective of this work was a preliminary estimate of the possible environmental significance of radon release from geothermal resource development. Measurements of radon in geothermal fluids made to study its tracer potential also permit a quantitative estimate of the source term. To place this estimate in proper perspective, measurements of natural radon release and ambient air concentrations are also required.

## Specific Objectives of this Study

The two basic goals of the project led to the definition of the following specific experimental objectives:

1) Selection and implementation of a method for radon measurement,
2) Test and evaluation of sampling techniques,
3) Actual field measurements of radon in various types of geothermal reservoirs.

Measurement Method--The radon measuring system was selected on the basis of three primary criteria: reliability, wide range of response, and adaptability to different types of geofluids. A secondary criterium was compatibility with available measurement equipment to minimize expense. Sample types included condensed steam, liquids with both radon and dissolved radium content, non-condensable gases including air, and rock fragments or drill cuttings.

Sampling Techniques--The sampling techniques used for geothermal wells were developed with several criteria in mind: ease of field operation, consistency, and simplicity of equipment for reliability. Methods for sampling ambient air and the flux of radon through soil surfaces were devised to achieve the second goal.

Survey Program--The survey program was established in cooperation with private industry and government agencies to obtain samples from different types of geothermal reservoirs and under varying conditions of well flow.

## Scope and Limitations of the Study

This project was undertaken as a component of a larger research program at Stanford University entitled "Stimulation of Geothermal Aquifers for Contributing to the Energy Requirements of the United States." Accordingly, one purpose of this preliminary study of radon was to provide a basis for defining promising areas for further investigation under the continuing research program. This purpose is reflected in the Conclusions.

Certain limitations were imposed by the institutional nature of existing geothermal resources development. Most of the present development is being undertakea by private industry. The highly competitive nature of the business requires that much well performance and production data remain confidential. This need for confidentiality is reflected in the manner that some of the data are reported. However, the significance of the data and the conclusions drawn from them are not affected.

# CHAPTER 2

## BACKGROUND AND THEORY

Some aspects of radon behavior under natural and laboratory conditions can be predicted from available knowledge of its fundamental properties. This chapter describes some basic physical-chemical characteristics of radon and summarizes the information on its natural occurrence. Several models of radon transport are presented as a theoretical base for possible tracer applications. Finally, environmental aspects of radon release from soil and natural gas production are reviewed.

### Radon Characteristics

Radon is the only natural radioactive gas that occurs in appreciable amounts in the hydrosphere and atmosphere. It is chemical. element number 86, a member of the noble gas family, the radon isotopes of masses 219, 220 and 222 are respective members of the $^{235}$U, $^{232}$Th and 238U natural decay chains. Two of them, $^{220}$Rn (actinon) and $^{219}$Rn (thoron), have half-lives of *54* seconds and **3.9** seconds respectively, too short to be of interest in this study.

The isotope most frequently used in earth science studies is $^{222}$Rn with a half-life of *3.824* days. **It** is continually produced by alpha decay of 1602-year $^{226}$Ra which is a member of the decay series beginning with 4.51 x $13^{9}$-year $^{238}$U. Radon decays by a chain of alpha and beta emitting radionuclides that lead to the stable isotope $^{206}$Pb. The genetic relations between the precursors and daughters of radon are **shown** in Figure **1**.

The activity, or disintegration rate, of an isotope is a first-order decay process given by

$$A = \frac{dN}{dt} - \lambda N \qquad (1)$$

where A = the activity (disintegrations/time)

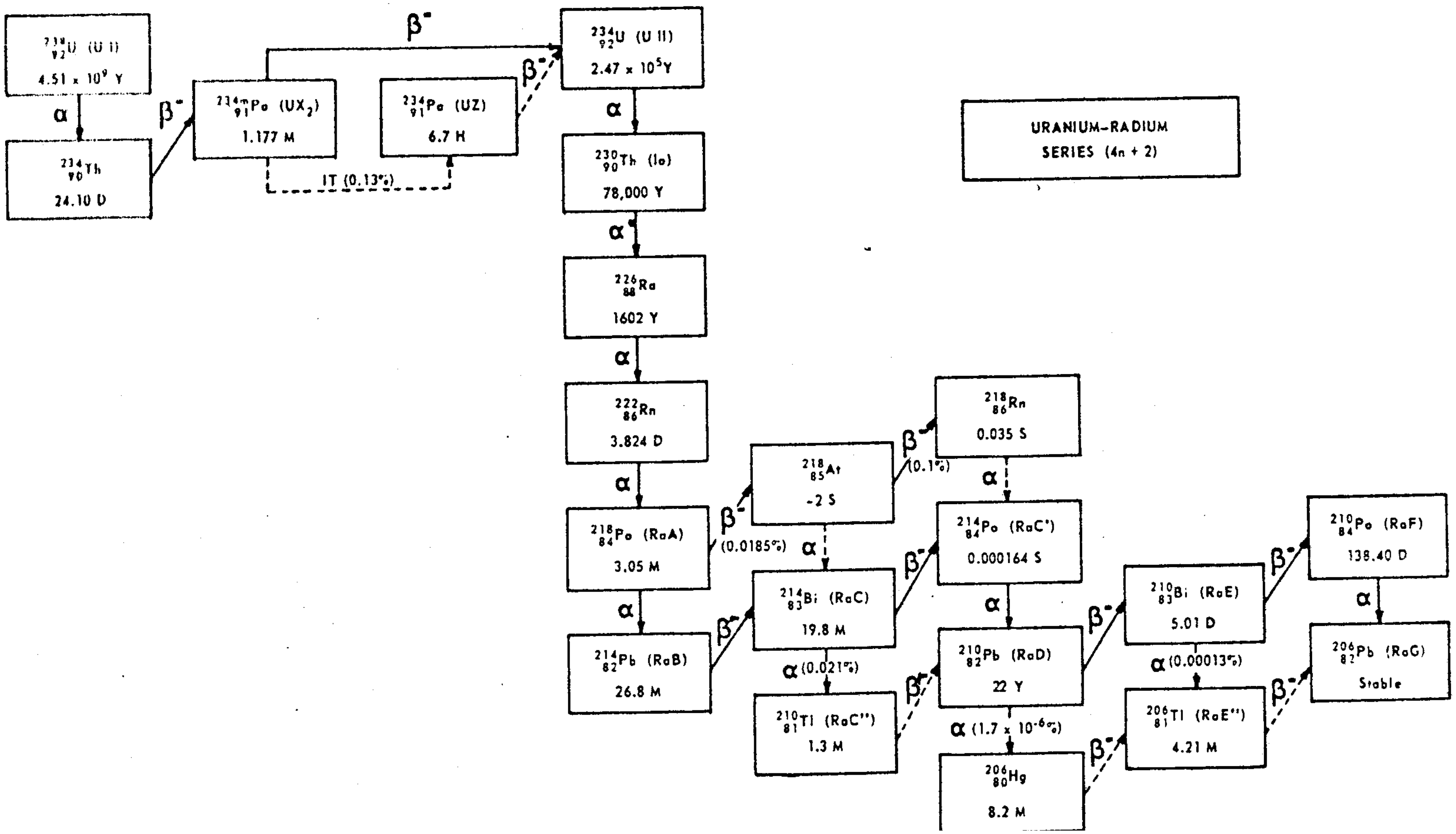

Figure 1. Genetic relationships of natural uranium-radium decay series.

$N$ = the number of atoms

$\lambda$ = the decay constant ($\text{time}^{-1}$) = $\frac{\ln 2}{T_{\frac{1}{2}}}$

$T_{\frac{1}{2}}$ = the half life of the isotope (time)

For a single pure isotope equation (1) can be integrated to give the relation between the activity after elapsed time, t, and the initial activity, $A_o$;

$$A = A_o e^{-\lambda t} \tag{2}$$

In a decay chain, however, the number of atoms of a given isotope is also determined by its production rate, due to decay of its parent. The rate of change of the number of atoms of a given isotope is

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \tag{3}$$

where the subscripts 1 and 2 refer to parent and daughter respectively. Assuming $N_o$ atoms of the pure parent present at t = 0, integration of equation (3) gives the number of daughter atoms present at time t:

$$N_2 = \frac{\lambda_1 N_o}{\lambda_2 - \lambda_1} \left[ e^{-\lambda_1 t} - e^{-\lambda_2 t} \right] \tag{4}$$

For radium as the parent and radon as the daughter this can be reduced to a simpler form because the decay constant for radium is very much smaller than that of radon:

$$A_{Rn} = A_{Ra} \left[ 1 - e^{-\lambda t} \right] \tag{5}$$

where $\lambda$ is the decay constant of radon. This relation is graphed in Figure 2 ana shows the growth of radon activity in relation to the activity of initially pure radium. It can be seen that secular equilibria? is approached in a period of about 30 days.

In our measurement technique, the relation between radon activity and the total alpha activity resulting from decay of radon and its daughter; $^{218}$Po and $^{214}$Po must be available. The relation is derived

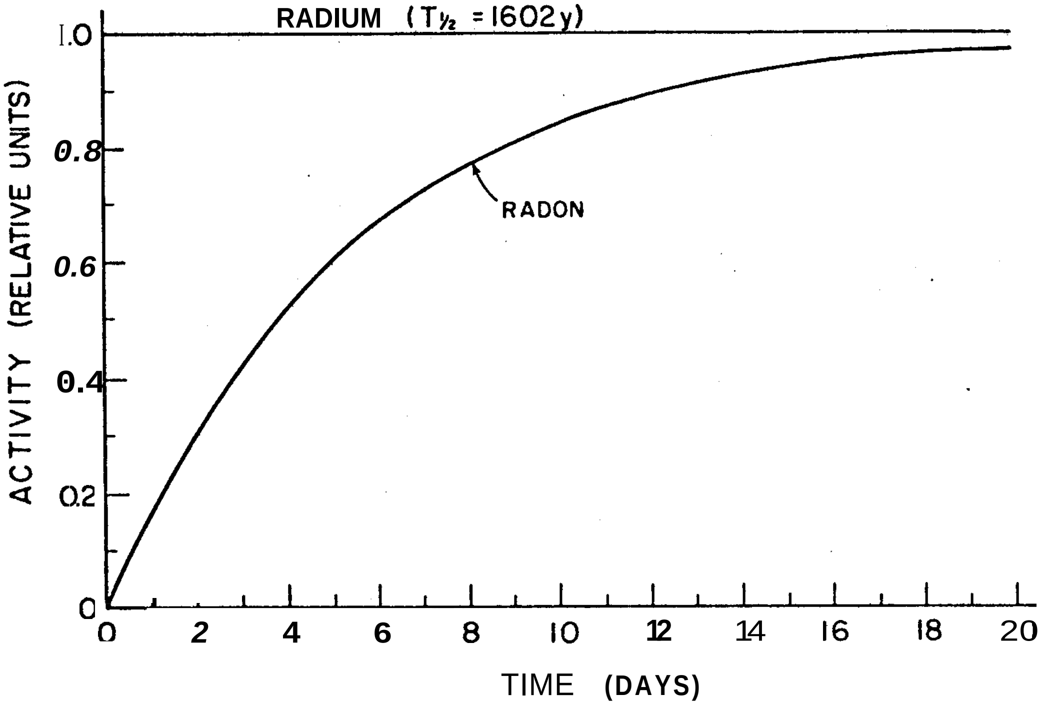

Figure 2. Radon Buildup, Radium **Parent.**

from the series of equations similar to equation (3) which can be integrated to yield one form of the Bateman equations (Kirby, 1973):

$$A_n = A_o \sum_{i=1}^{n} K_i e^{-\lambda_i t} \qquad (6)$$

where $K_1 = \prod_{j=2}^{n} Q_{1,j}$ and $K_i = -Q_{1,i} \prod_{j=2}^{n} Q_{i,j}$ for $j \neq i$; $i = 2,3,\ldots n$

with $Q_{i,j} = \dfrac{\lambda_j}{\lambda_j - \lambda_i}$ .

$A_o$ is the initial activity of the first member of the series and the subscript n refers to the position in the series.

Computer programs are available to solve these equations and compile tables of factors for the natural decay chains covering useful time periods (Kirby, 1973). Two of these tables for initially pure radium and radon are included in Appendix A. The growth of alpha activity resulting in an initially pure radon source is noted in Figure 3. Some pertinent chemical properties of radon are summarized in Table 1 (from Cook, 1961).

Table 1

Properties of Elemental Radon

| | | |
|---|---|---|
| Atonic Mass | 220.0114 | |
| Density (273°K, 1 atm.) | 9.73 g/l | |
| Normal Boiling Point | 211°K | |
| Heat of Vaporization | 4325 cal/mole | |
| Normal Melting Point | 202°K | |
| Solubility in $H_2O$ (1 atm.) | $cm^3$(STP)/kg | Temp. (°K) |
| | 510 | 273 |
| | 230 | 293 |
| | 169 | 303 |
| | 139 | 313 |
| | 114 | 323 |
| | 96 | 333 |
| | 86 | 343 |

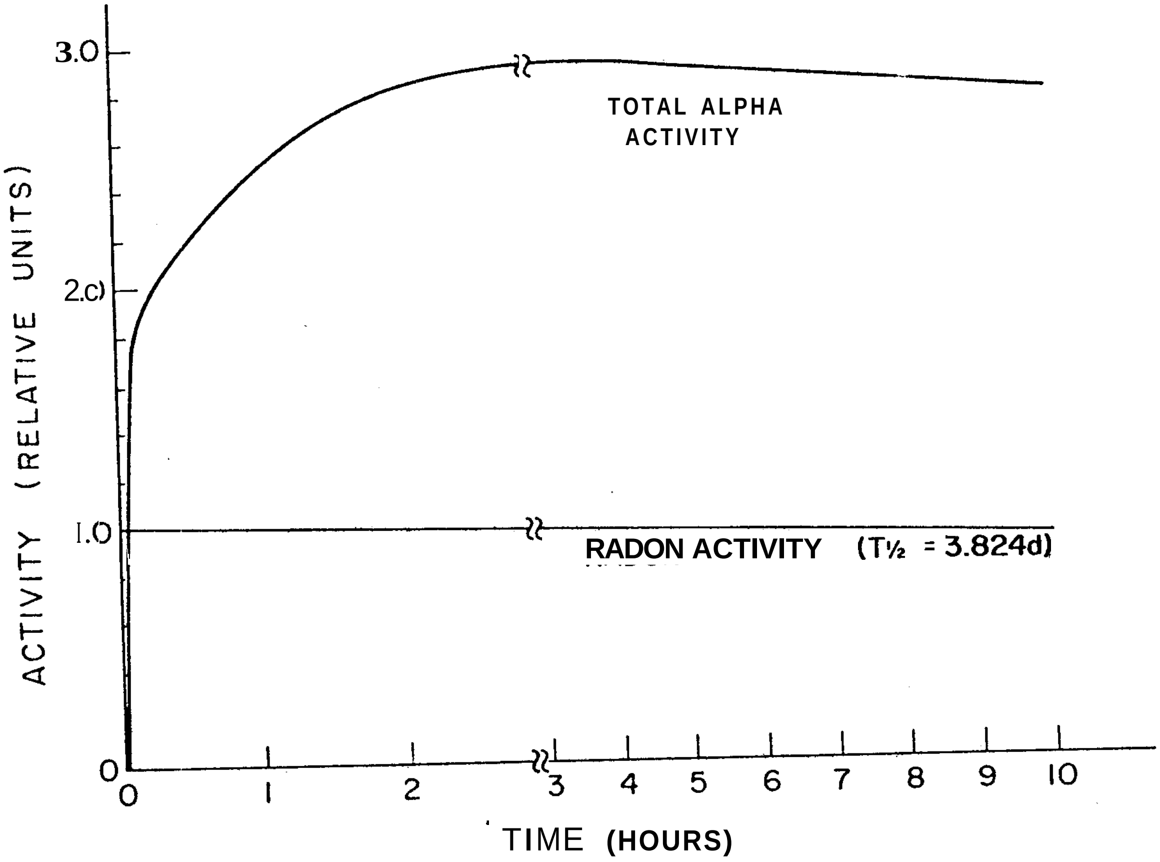

Figure 3. Radon daughter buildup.

A useful form of radon solubility data is its distribution coefficient (the ratio of concentration of radon in water to the concentration in gas). This ratio as a function of temperature is shown in Figure 4 (after Rogers, 1958). Solubility is markedly reduced when electrolytes are in solution (Rogers, 1958).

Radon, like other noble gases, may be adsorbed on activated charcoal. Adosrption is greater for the heavier gases, and is inversely related to temperature for a given gas. Data for noble gas adsorption on activated charcoal is given in Table 2.

Table 2
Adsorption of Noble Gases

| | Heat of Adsorption** | | Temperature for Adsorbing 50g Gas on 100g Activated Charcoal |
|---|---|---|---|
| Gas | (kcal/mole) | At Approx. Temp. (°K) | |
| He | 0.54 | very low | * |
| Ne | 1.13 | 77 - 91 | 85 |
| Ar | 3.93 | 168 | 152 |
| Kr | 5.32 | 198 - 223 | 203 |
| Xe | 8.74 | 248 | 267 |
| Rn | 13.5 | (extrapolated) | |

*Almost no He adsorbed at 77°
**On activated charcoal
(Source: Cook, 1961)

Presence of Radon in Geologic Settings--The occurrence of radon is entirely dependent on its continual production from radium decay; it cannot accumulate to levels greater than radioactive secular equilibrium. The presence of radon in geofluids, then, is determined by the occurrence of radium in subsurface materials and the transfer of radon into the fluid.

Controls on the Occurrence of Radium--The occurrence of radium is in turn dependent on its own geochemistry and that of its precursors,

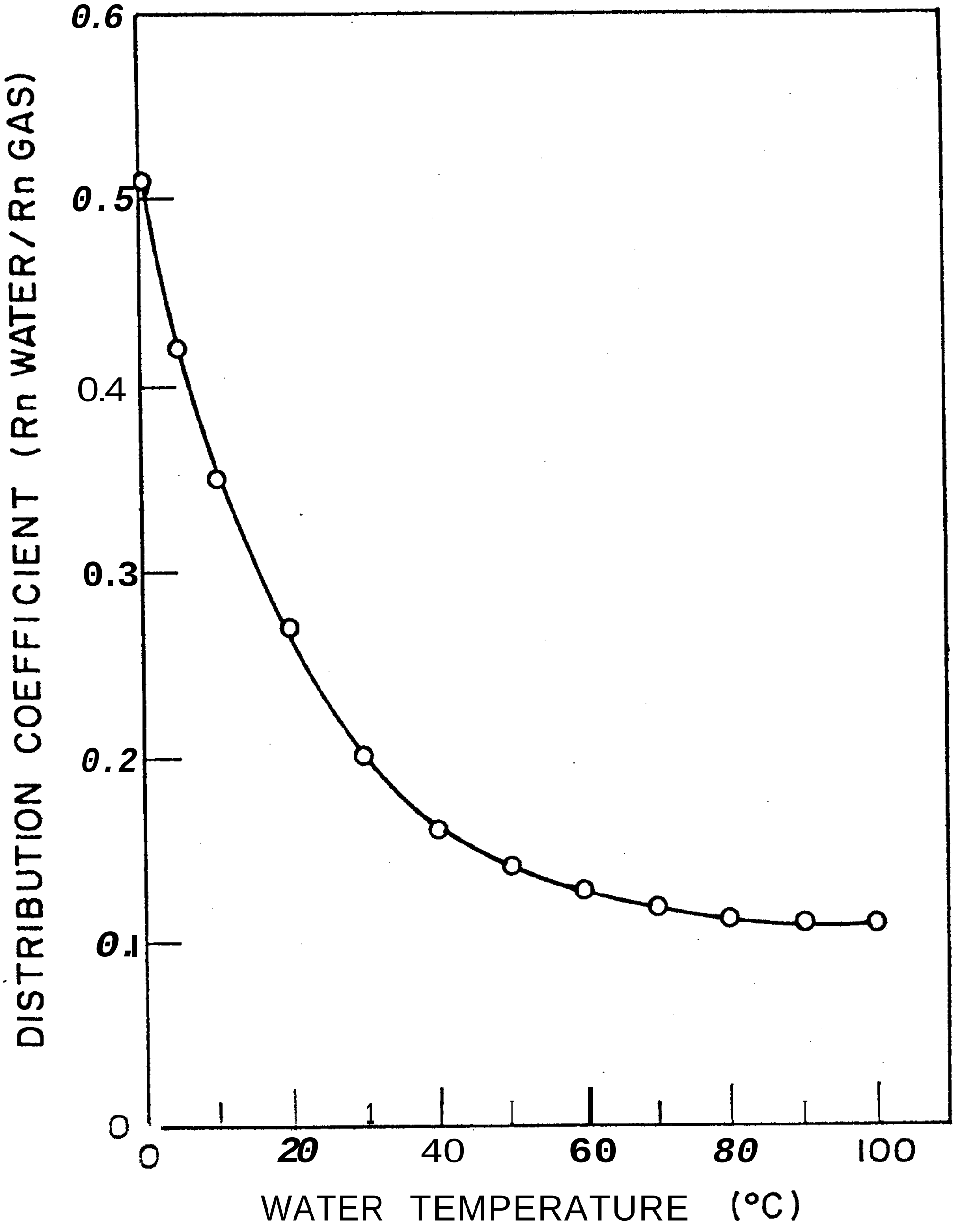

Figure 4. **Radon** distribution coefficient as a function of temperature.

uranium and thorium. The hydrogeochemistry of radium is complex and neither well understood nor well documented (Tanner, 1964b). Some general treatment of the controlling conditions appears in the Soviet literature on prospecting methods for uranium. The following discussion is based on a compendium of such work (Tokarev and Shcherbakov, 1956).

Natural rock may be grouped according to the content of radioactive substances as average or above average. Table 3 gives one set of typical values for rocks with normally dispersed radioactive elements.

Table 3

Average Content of Radioactive Elements

| Rock | U (ppm) | Th (ppm) | Ra ($10^{-6}$ ppm) |
|---|---|---|---|
| Magmatic | | | |
| Acid | 9.10 | 20.5 | 3.01 |
| Median | 6.20 | 16.4 | 2.57 |
| Basic | 3.20 | 5.60 | 1.28 |
| Sedimentary | | | |
| Sandstone | 4.20 | 6.00 | 1.50 |
| Clay | 4.50 | 13.0 | 1.30 |
| Limestone | 2.70 | 0.50 | 0.50 |

Rock with larger concentrations are subdivided into three categories:

A. Increased but uniformly dispersed content, as often found in shales, lignite, sandstones, peat, and iron-silicate rocks. The increased deposition is due to such processes as adsorption, ion exchange, co-precipitation, and reduction.

B. Ore concentrations of uranium and radium, frequently found in hydrothermal zones of tectonic dislocation. Major processes are transport in solution in the presence of high $CO_2$ content and deposition as $CO_2$ is lost or by redox reactions especially with iron.

C. Secondary concentrations of radium, which are usually local formations, associated with adsorptive formations of radium in water conducting fissures, and in calcareous tuff and iron-manganese deposits.

Radioactive equilibrium is often disrupted because geochemical cycles can fractionate radium from its precursors. Radium is a homolog of the alkaline earth elements Mg, Ca, and Ba. It is invariably found with all barium compounds and coprecipitates with $CaCO_3$. However, coprecipitation of Ra does not occur with $CaSO_4$ or with halides of alkaline metals. Radium can be strongly adsorbed by clayey and organic matter, and by iron and manganese hydroxides. The solubility of RaCl is high; therefore highly mineralized Na-Ca-Cl waters can carry significant amounts of dissolved radium.

Release of Radon to Geofluids--While radon is continually produced by radium associated with rock materials, only a fraction of the gas may actually be released to geofluids. This is because newly formed. radon ions may be entrapped in the rock and never reach the fluid interface.

The location of the parent radium atom and the recoil energy imparted to the radon ion are key factors controlling release. The energy of the recoiling radon ion is given by:

$$E_r = \frac{M(He)}{M(Rn) + M(He)} Q \qquad (7)$$

where M(He) and M(Rn) are the masses of the alpha particle and the radon atom respectively, and Q is the energy released by radium decay. For Q = 4.79 MeV, the radon recoil energy = 0.086 MeV. This kinetic energy is lost to the surrounding media at a rate determined by the material. In air the range is about $6 \times 10^{-3}$ cm, in water about $1 \times 10^{-5}$ cm, and in rock of average density about $3 \times 10^{-6}$ to $4 \times 10^{-6}$ cm (Tanner, 1964; Andrews and Wood, 1972).

Andrews and Wood (1972) discuss four possible mechanisms of radon release fron minerals: (1)recoil directly into the fluid, (2) diffusion from within crystal lattices of the mineral, (3) recoil. into crystal mosaic boundaries, dislocation planes, or grain boundaries followed by rapid diffusion to particle surfaces, and *(4)* release into or from relatively porous secondary phases followed by rapid diffusion to the surface.

The direct recoil processes are limited by the recoil path length;

only those ions able to reach the surface in distances less than about 3.5 x $10^{-6}$ cm will be released. Calculation assuming a flat surface mineral shows that about 23.5 per cent of radon ions produced by radium decay within a depth equal to the recoil range will be released. For assumed spherical particles with uniformly distributed radium, the overall percentage release is given by 4.9/d with d = particle diameter in micrometers (Andrews and Wood, 1972).

Because lattice diffusion is extremely slow, the second mechanism can be discounted (Tanner, 1964a). Any release by this mechanism would be expected to follow the specific surface area which is proportional to 1/d.

Diffusion along imperfections and grain boundaries is relatively fast, however, and would be expected to be dependent on the length of these boundaries intersecting the surface. This will be proportional to the square root of the specific surface area and therefore proportional to $1/d^2$. Experimental results for sands, sandstone, and limestone particles show this predicted relationship (Andrews and Wood, 1972).

The mechanism of release from secondary phases, such as cementing materials, is evidently also important and corresponds to expectations of secondary radium deposition in films or crusts (Tanner, 1964a). Andrews and Wood (1972) present data to support this and suggest that a $1/d^2$ proportion observed for particles from a cemented sandstone probably relates to the grains of the cementing phase. Percentage release of radon becomes almost independent of particle size for this heterogeneous cemented material when d exceeds 4.5 x $10^{-2}$ cm.

The fluid present in the rock pores and voids influences the amount of radon available for transport. In tightly compacted materials, ions escaping the surface of one grain may bury themselves in adjacent grains. If water fills the voids, the recoiling ions are more likely to be stopped in the fluid. This effects is often observed (Tanner, 1964a). Conversely, water may reduce the net amount of radon release in the absence of fluid notion because the molecular diffusion is much less in water than in air. The diffusion lengths for radon in air and water are 218 and 2.18 cm respectively (Andrews and Wood, 1972).

Only limited fluid motion is necessary to minimize radon concentration gradients away from a rock surface. A velocity of $10^{-3}$ cm/sec is sufficient to maintain concentrations at 1 meter within 80 percent of the surface value (Andrews and Wood, 1972).

Radon release from some materials is enhanced by weathering, chemical corrosion, and intensive fracturing on a microscopic scale. This may be explained by recoil into liquid filled spaces or diffusion along imperfections (Tanner, 1964a). The importance of such changes will obviously be closely related to the distribution of radium in the rock matrix.

## Transport through Fractured and Porous Media

The amount of radon contained in a unit of fluid that has passed through a geologic formation depends on three important factors: the release rate of radon from a unit volume of rock, the volumetric relation between the rock and fluid, and the time spent by the fluid in the rock. Simple flow models can illustrate the theoretical influence of each factor and provide some basis for analysis of experimental results.

Hydrologic Transport--Radon transport in a liquid phase will be considered first. Models for linear and radial geometry can be formulated from assumptions concerning: (1) homogeneous, isotropic porous media, (2) uniformly distributed radium, i.e. homogeneous emanating power, (3) steady-state flow conditions, (4) incompressible fluid, and (5) loss of radon from the fluid oniy by radioactive decay.

Linear Flow Model--The simplest geometry is a linear system of uniform cross section as shown in Figure 5. The system has two sections of rock, one with significant emanating power, the other with essentially zero emanating power.

For steady state flow the amount of radon transported out of the emanating rock section can be deduced by the production rate in each incremental volume and the decay during the time required for transport.

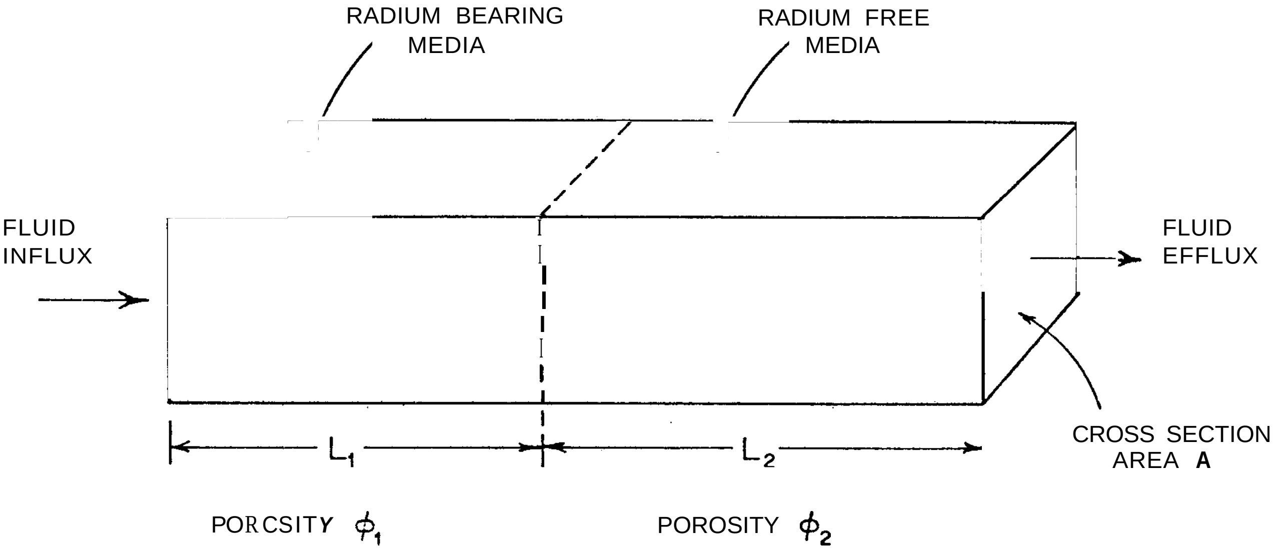

Figure 5. Linear **flow model.**

The incremental rate of radon atoms transported across the right hand face of the radium bearing rock due to a volume of rock x units to the left is:

$$dR = EA \exp(-\frac{\lambda A\phi_1 x}{Q})dx \qquad (8)$$

where R = the number of radon atoms per unit time

E = the emanating power of the rock, pCi/$cm^3$ of radium (the production rate of radon atoms)

A = the cross sectional area, $cm^2$

$\lambda$ = the decay constant for radon, $sec^{-1}$

$\phi_1$ = the fractional porosity of the rock

Q = the fluid flow rate, $cm^3$/sec

Integration of equation 2 over the limits zero to L leads to the expression:

$$R = \frac{EQ}{\lambda\phi_1}\left[1 - \exp(-\frac{\lambda A\phi_1 L_1}{Q})\right] \qquad (9)$$

The activity concentration of radon in the fluid is obtained by multiplying R by the decay constant and dividing by the volumetric flow rate to give:

$$C = \frac{E}{\phi_1}\left[1 - \exp(-\frac{\lambda A\phi_1 L_1}{Q})\right] \qquad (10)$$

where C is the activity concentrationof radon in the fluid, pCi/$cm^3$. Note that this equation is similar to equation (5) and has the graphic representation shown in Figure 2.

The radon concentration expected at the outflow face of the non-radium bearing rock requires an additional decay factor for transport time through length $L_2$ 2nd is given by

$$C = \frac{E}{\phi_1}\left[ - \exp(-\frac{\lambda A\phi_1 L_1}{Q})\right] \exp(-\frac{\lambda A\phi_2 L_2}{Q}) \qquad (11)$$

Equation (11) shows that the maximum concentration of radon approaches $E/\phi_1$ when the residence time ($A\phi L/Q$) in the radium bearing rock is long and that in the non-radium bearing rock is small. The concentration should be exponentially dependent on flow rate. For example, if there is a significant length of non-radium bearing rock the decay term would be reduced by an increased flow rate. An increased radon concentration resulting after pumping a well in a region where gravitational flow predominates is an instance of this situation which may be an indicator of an ore concentration (Tokarev and Shcherbakov, 1956). If the length of radium bearing rock is relatively short and there is no significant interval for decay, then the concentration would be expected to decrease with increasing flow rate. Or, if the radium bearing rock extends for large distances and there is no significant decay interval, then the concentration would be independent of flow rate.

Radial Flow Model--Figure 6 shows the geometry for the radial flow model. Only rock with uniform radium content is considered. For steady-flow, the rate of radon atoms flowing into the well bore from a cylindrical. shell volume element is given by the production rate in that shell reduced by the decay during transport:

$$dR = E \exp(-\lambda t_r) dV \qquad (12)$$

where $t_r$ = the time for transport from r to $r_w$

$dV$ = the incremental volume, $2\pi hr\,dr$

The transport time, $t_r$, can be computed from the flow velocity in radial flow obtained from either the Dupuit or Jacob semi-log formulation:

$$v = \frac{dr}{dt} = \frac{Q}{2\pi rh} \qquad (13)$$

Integration between r and $r_w$ gives:

$$t_r = \frac{\phi\pi h}{Q}(r^2 - r_w^2) \qquad (14)$$

Making the appropriate substitutions in equation (12) and integrating from $r_w$ to $r_e$ leads to:

$$R = \frac{EQ}{\lambda\phi}\left\{1 - \exp\left[-\frac{\lambda\phi\pi h}{Q}(r_e^2 - r_w^2)\right]\right\} \qquad (15)$$

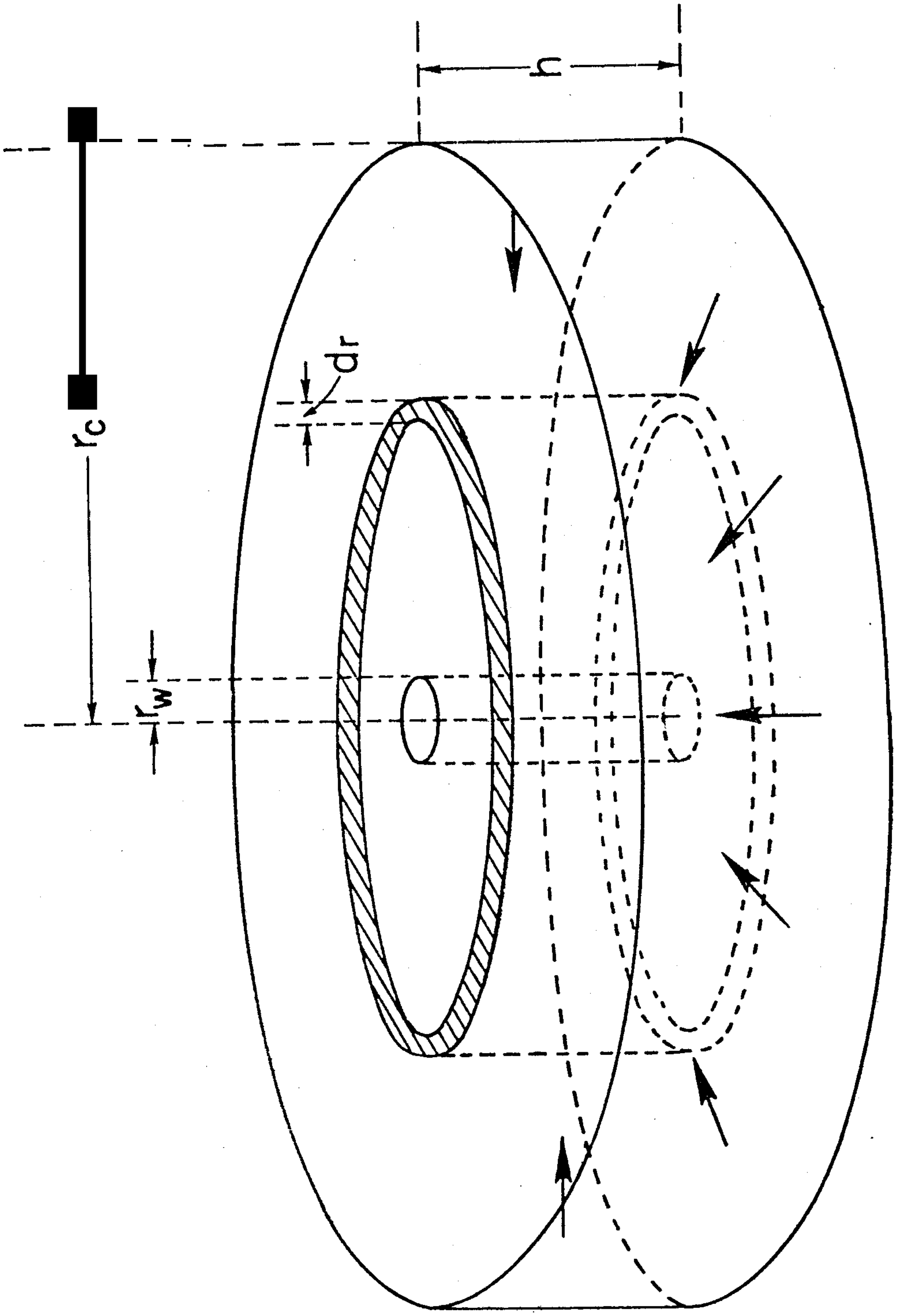

Figure 6. Radial flow mobel.

as the rate of radon atoms transported into the wellbore. The radon activity concentration is obtained by multiplying by the decay constant and dividing by the fluid flow rate:

$$C = \frac{E}{\phi}\left\{1 - \exp\left[-\frac{\lambda\phi\pi h}{Q}(r_e^2 - r_w^2)\right]\right\} \tag{16}$$

Qualitatively, the result is similar to the linear flow model [equation (10)]; the difference being the form of the apparent time of flow which determines the extent of approach to the maximum concentration. It should be noted that $r_e$, the effective radius of influence, will be related to the permeability of the medium and therefore the difference in Piezometric head required to maintain a given flowrate, Q (see e.g. Davis and Dewiest, 1966). For typical values of $r_e$ on the order of 500 to 1000 ft, and a formation thickness of 200 feet and porosity 0.2, the flowrate would have to be in excess of 100,000 gal/hr to make the exponential term larger than 0.1. Thus, for relatively low flow rates in a large reservoir, the concentration of radon would not be expected to depend strongly on flowrate.

Compressible Fluid Model--Sakakura, Lindberg, and Faul (1959) derived a radial flow model for the transport of radon in natural gas. They first considered a cylindrical shell radon source, and then integrated the resulting expression to represent an extended source. The basic geometry and assumptions are the same as the liquid radial flow model but they also accounted for the fluid compressibility. Their solution for steady-state flow in a large reservoir with uniform emanating power throughout is:

$$C_o = \frac{T_w P_o E}{T_o P_w \phi\alpha}\left(1 + \frac{\omega}{2}\sqrt{\frac{\pi}{\alpha}}\right) \tag{17}$$

where $C_o$ = activity concentration of radon in the gas at selected standard conditions

T = temperature

P = pressure, subscripts w and o referring to wellhead and standard conditions respectively

$$\alpha = 1 + \omega(\log \frac{R_o}{r_w} + \frac{1}{2})$$

with $R_o = (\frac{Q}{\pi\phi h\lambda})^{\frac{1}{2}}$

$$\omega = \frac{P_s^2 - P_w^2}{2P_w^2 \log(r_e/r_w)}$$

with $P_s$ = static pressure with no flow

$P_w$ = wellhead flowing pressure

The other terms E, $\phi$, $\lambda$, $r_w$, and $r_e$ are used as previously defined.

Depending on the pressure drop needed to maintain a given flow, the concentration of radon in the gas will depend more or less strongly on the flowrate. When high pressure drops are needed for large flow rates, the concentration will be expected to decline with increasing flowrates. For low flow rates from a large reservoir, the concentration would be almost independent of flowrate.

Sakakura, et al. (1959) also derived a general solution of the radon activity concentration as a function of time for transient flow assuming that a gas well has been shut in for a long period. They suggest that complete numerical evaluation of the solution is not warranted because reservoir parameters are never sufficiently well described. However, it is possible to obtain a useful solution of the distance to the nearest radon source; experimental data from 5 gas wells indicate that location is at or within a few feet of the wellbore (Sakakura, et al., 1959).

## Possible Applications

The preceeding theoretical discussion suggests some ways of interpreting observations of radon concentration at a wellhead in terms of geologic properties and flowing conditions, both qualitatively and quantitatively.

The ratio E/$\phi$ appears in each model as a source term, hence an important determinant of concentration in the fluid. E is controlled by geochemical conditions of radium deposition and possibly physical microstructure properties of the rock. Thus radon concentration measurement may become another geochemical tool to help define and compare different geothermal systems. For example, Wollenberg (1974) shows a preferential correlation of radium activity with $CaCO_3$ hot springs in Nevada and notes that most but not all of the $^{222}Rn$ activity derives from such deposits. Wollenberg suggests that such information will help evaluate potential geothermal sites and be useful in gaining understanding of subsurface flow processes. Chendyntser (1970) shows how ratios of radon to other isotopes can be used to determine origins and ages of thermal waters.

Changes in the rock structure can be expected to influence radon concentration. Stimulation processes can be expected to affect both micro-properties, such as microfractures, and macro-properties, such as bulk porosity. Such changes can affect both E and $\phi$, possibly to different degrees.

An indication of possible changes comes from two kinds of measurements. A few radon measurements were taken during the Rulison stimulation experiment in which a 43 kt nuclear explosive was detonated on 10 September 1969 in the Mesaverde formation of the Rulison, Colorado field at a depth of 8426 feet. A summary of the available radon data (Kruger, 1974) is given in Table 4.

Table 4

Radon Data from the Rulison Experiment

| Sample Identification | $^{222}Rn$ Concentration (pCi/1) |
|---|---|
| Preshot, R-EX Well | |
| 28 October 1968 | 20.8 |
| Postshot Flaring | |
| 1 August 1968 | 15. |
| 7 October 1968 | 7.1 |
| 2nd Production Period | |
| 2-13 December 1968 | 21.1 |

The data involve large uncertainties of up to ±100% and can be interpreted only speculatively. One interpretation is that during the flaring tests the reduced concentration reflects the large increase in porosity in the rubble chimney, overwhelming any possible increase in emanating power. After the large production tests the value may be reflecting an influx of more gas from the less disturbed parts of the formation.

The second indication of changes in radon concentration resulting from subsurface geologic changes has been reported in relation to earthquake prediction (Hammond, 1973). Increases in radon concentrations in groundwater were noted on two occasions prior to earthquakes in the Tashkent region. The increases are tentatively explained in context of the dilatancy model currently being studied as an earthquake mechanism. It involves changes in pore space, fluid pressures, and water movement, and can be expected to result in increased release and more rapid transport of radon.

It is possible that some quantitative measurement of formation properties may be obtained from radon concentration observations. It should be possible to obtain a value for the $E/\phi$ ratio by measurement of the radon concentration in the first formation fluid produced from a well that has been shut in for a long enough period to insure secular equilibrium, i.e. about a month. This initial concentration would not be influenced by flowing conditions because no significant decay should occur in the time for the first formation fluid to reach the surface. Then, if the well can be produced at a high enough rate for a long period, on the order of a month to establish radioactive equilibrium, a decreased concentration would be expected because the terms modifying $E/\phi$ in 2.15 or 2.17 would be less than 1.0. All of the factors in these terms except $\phi$ or $r_2$ and h are either known or can be estimated. For example, in 2.16, $\lambda$, Q, and $r_w$ would be known, $r_e$ can be estimated from pressure measurements in observation wells or on the basis of well spacing, and h may be known from well logging. The magnitude of the term in brackets is given by the ratio of the concentrations at the start of flow and at final steady-state. Thus the magnitude of $\phi$ can be evaluated if h is known; or, the magnitude of $\phi h$ can be found if h is not known. Either the porosity or the porosity-thickness product are important reservoir parameters, especially for estimating reserves; and are generally obtainable only by well interference testing. The technique assumes a constancy of E and the possibility of producing a well. at a high flowrate. Smith, et al. (1961) report a 24 per cent decrease in radon content of water pumped from an industrial well during a 6 day period which indicates the feasibility of achieving adequate production rates.

## Survey of Radon Concentrations in Geofluids

A brief review of literature values for radon concentrations in various geofluids was made to gain perspective on the range of concentrations that might be expected in geothermal reservoir fluids. Reported values for ground water, hot springs and geothermal zones, and natural gas are summarized in Tables 5, 6, and 7 respectively.

Table 5

Radon Concentrations in Groundwaters

| Source | Average or Range of Concentration (pCi/l) | Reference |
|---|---|---|
| Maine, drilled wells | 17,100 | Smith, et al., 1961 |
| Maine, dug wells | 14,700 | Smith, et al., 1961 |
| New Hampshire, drilled wells | 32,100 | Smith, et al., 1961 |
| New Hampshire, dug wells | 5,900 | Smith, et al., 1961 |
| Colorado, spring | 260,000 | Smith, et al., 1961 |
| Illinois, wells & springs | 50-2,900 | Smith, et al., 1961 |
| Missouri, mineral spring | 430 | Smith, et al., 1961 |
| Italy, dolomitic & calcareous aquifers | 50-10,200 | Margi & Tazioli, 1970 |
| Illinois, wells | 60-500 | Lucas, 1964 |
| England, sandstone aquifer | 115-890 | Andrews & Wood, 1972 |
| England, limestone aquifer | 38-640 | Andrews & Wood, 1972 |
| USSR, sedimentary rocks | 100-5,000 | Tokarev & Shcherbakov, 1956 |
| USSR, acid magmatic rock | 1,000-40,000 | Tokarev & Shcherbakov, 1956 |
| USSR., cranium deposits | 5,000-5,000,000 | Tokarev & Shcherbakov, 1956 |
| Utah, artesian wells | 50-1,800 | Tanner, 1964b |

## Table 6

### Radon Concentrations in Hot Spring and Geothermal Waters

| Source | Range of Concentration (pCi/l) | Reference |
|---|---|---|
| England, thermal spring | 1,380-2,400 | Andrews & Wood, 1972 |
| Japan, thermal springs | 25,000-73,000 | Kikkawa, 1954 |
| Israel., thermal springs | 2,900-7,420 | Mazor, et al., 1973 |
| USSR, hot springs | 500-100,000 | Chirikov, 1971 |
| New Zealand, fumarole condensate | 7,000-340,000 | Belin, 1959 |
| Arkansas, hot springs | 100-30,000 | Kuroda, et al., 1954 |
| Arkansas, potash hot springs | 6,000-80,000 | Kuroda, et al., 1954 |

## Table 7

### Radon Concentrations in Natural Gas

| Source | Range of Concentration (pCi/l) | Reference |
|---|---|---|
| Colorado-New Mexico | 0.2- 160 | Johnson, et al., 1973 |
| Texas, Kansas, Oklahoma | 5-1450 | Johnson, et al., 1973 |
| California | 1-100 | Johnson, et al., 1973 |
| Colorado-New Mexico, San Juan Basin | 0.2-160 | Bunce & Sattler, 1966 |

Wide variations occur for all types of fluids. In addition, the concentrations from a given source may change over time (e.g. Kuroda, et al., 1954; Bunce and Sattler, 1966), in response to flow rate (e.g. Smith, et al., 1961), and in correlation with atmospheric pressure and precipitation (e.g. Kikkawa, 1954).

## Environmental Considerations

Any evaluation of environmental effects of man's activities must be related to the occurrence of radon under natural conditions. The natural ambient air concentrations of radon, and its release rate from natural land surface are two important factors.

Natural air concentrations of $^{222}$Rn may vary widely from one locale to another depending on soil and atmospheric conditions. The average atmospheric content from 1 to 4 meters above the ground is about 0.3 pCi/l; minima and maxima, respectively, can be 0.1 to 10 times that amount (Johnson, et al., 1973; Eisenbud; 1963).

The continual release of radon from soil surface maintains the atmospheric concentration. This radon flux can be theoretically described as a diffusion process and related to the emanating power of the soil material (Wilkening and Hand, 1960). However, the flux may be sharply changed by rainfall, ice or snow cover, and atmospheric pressure changes (Tanner, 1964a). More exact models have been proposed to account for these effects (e.g. Clements and Wilkening, 1974). Of most interest here, however, is actual data reported for radon flux. A compilation of nearly 1000 measurements throughout the world lead to an average value of 0.75 atoms/cm$^2$-sec or 4.25 x $10^{-5}$ pCi/cm$^2$-sec (Wilkening, et al., 1972). Integration of the flux for different soil types leads to an estimated world-wide release of 52 Ci/sec, or about 4.5 x $10^6$ Ci/day.

Natural gas production results in some added release of radon. Johnson, et al. (1973) have studied this release for potential health effects. They conclude that even though much natural gas is burned in homes, thereby releasing radon into a confined environment, the added radon raises average indoor background radon concentrations by about 1.1 to 1.2 per cent. Outside, even in large metropolitan areas prone to inversions, the radon level is raised no more than 0.6 per cent. Taking their factors of 20 pCi/l of radon in natural gas at point of use and annual gas sales of 19.5 x $10^{12}$ standard cubic feet, one can estimate overall radon release due to natural gas as 30 Ci/day. Johnson, et al. (1973) conclude that the use of natural gas containing $^{222}$Rn does not contribute significantly to health effects in the United States.

# CHAPTER 3

# MEASUREMENT METHODS

## Radon Detection and Measurement

Radon can be measured by several techniques based on detecting alpha particles from radon and its daughters, beta particles or gamma rays from radon daughters. The more common detectors include ionization chambers or scintillation phosphors to detect alpha particles, and scintillation crystals to detect gamma radiation. Liquid scintillation detectors are also used.

To measure low levels of radon, some method of concentration is often applied. For example, in sampling of the atmosphere, to obtain adequate levels of radon (Cohen, et al., 1972), air is drawn for a full hour through a two-filter system in which the alpha decay of radon daughters is detected. Alternatively, radon from air and soil gas samples may be accumulated in a condenser cooled by liquid oxygen. It is then transferred to an ionization detector for activity measurement (Wilkening and Hand, 1960). For measurement of radon concentrations found in natural waters, ionization chambers with volumes of about 4.2 1 have been used to measure the activity of radon bubbled out of the sample by a carrier gas (Rogers, 1958). Radon can be adsorbed on activated charcoal from natural fluid flow, both liquid and gas, in the field. The gamma-ray activity of radon daughters can be counted with a portable NaI(Tl) crystal detector (Magri and Tazioli, 1970). Adsorption of radon onto cooled activated charcoal has been used by several workers. For example, Steheny, et al. (1955) determined the characteristics of activated charcoal at dry ice temperature for separation of radon from breath samples. Others include Lucas (1964) who developed a low-background ZnS scintillation counter (1957) for radon and radium emanation studies, and Andrews and Wood (1972) who designed a somewhat different ZnS based counter. Detectors of the Lucas design with a high counting efficiency are commercially available.

From the criteria outlined in Chapter 1, the system chosen for this work was designed to provide low background, adaptability to a variety of geothermal fluid samples, and ease of operation. The system consisted of a cooled-charcoal adsorption line for extracting radon from the samples and a measurement system based on the ZnS scintillator flasks, described by Lucas (1964).

Extraction System--A schematic illustration of the extraction system is shown in Figure 7. The process consists of adsorption of radon on charcoal cooled to -80°C, followed by thermal desorption at 400°C, and transfer in helium carrier gas into the scintillation detector flask. The system was constructed from standard glass vacuum components connected by ground glass joints to permit easy disassembly for cleaning.

A summary of the extraction process is useful in describing the function of each component. The cold trap for water and the adsorption trap for radon are cooled to -80°C in dry ice baths of nonflamable Freon TA. Stopcocks A, C, and E are opened; all others are closed. Needle valve D is used to control the entry of the radon-containing gas into the system at a rate of about 1 liter/min. Carrier gases at pressures less than one atnosphere are drawn through the traps by a vacuum pump, and gases at pressures greater than one atmosphere are vented to the atmosphere through stopcock E. Water is removed in the cold trap filled with copper turnings to provide surface area and thermal conductivity. Carbon dioxide is absorbed on ascarite (NaOH on asbestos) in the second trap. For samples containing large amounts of $CO_2$ a gas scrubber with KOH solution is included in the line just before the inlet.

Radon is adsorbed quantitatively in the third trap which contains 20 g gas-adsorption grade charcoal, 7-14 mesh in size, made from cocoanut shells. When the carrier gas has been flushed through the system, stopcocks A and C are closed, and any remaining traces of carrier gas are pumped out of the adsorption trap. The dry ice bath is removed and the trap warms to room temperature. An aliquot of helium counting gas is let into the trap from the He reservoir and the trap is heated to about 400°C by a metallic film heating element bonded onto the glass.

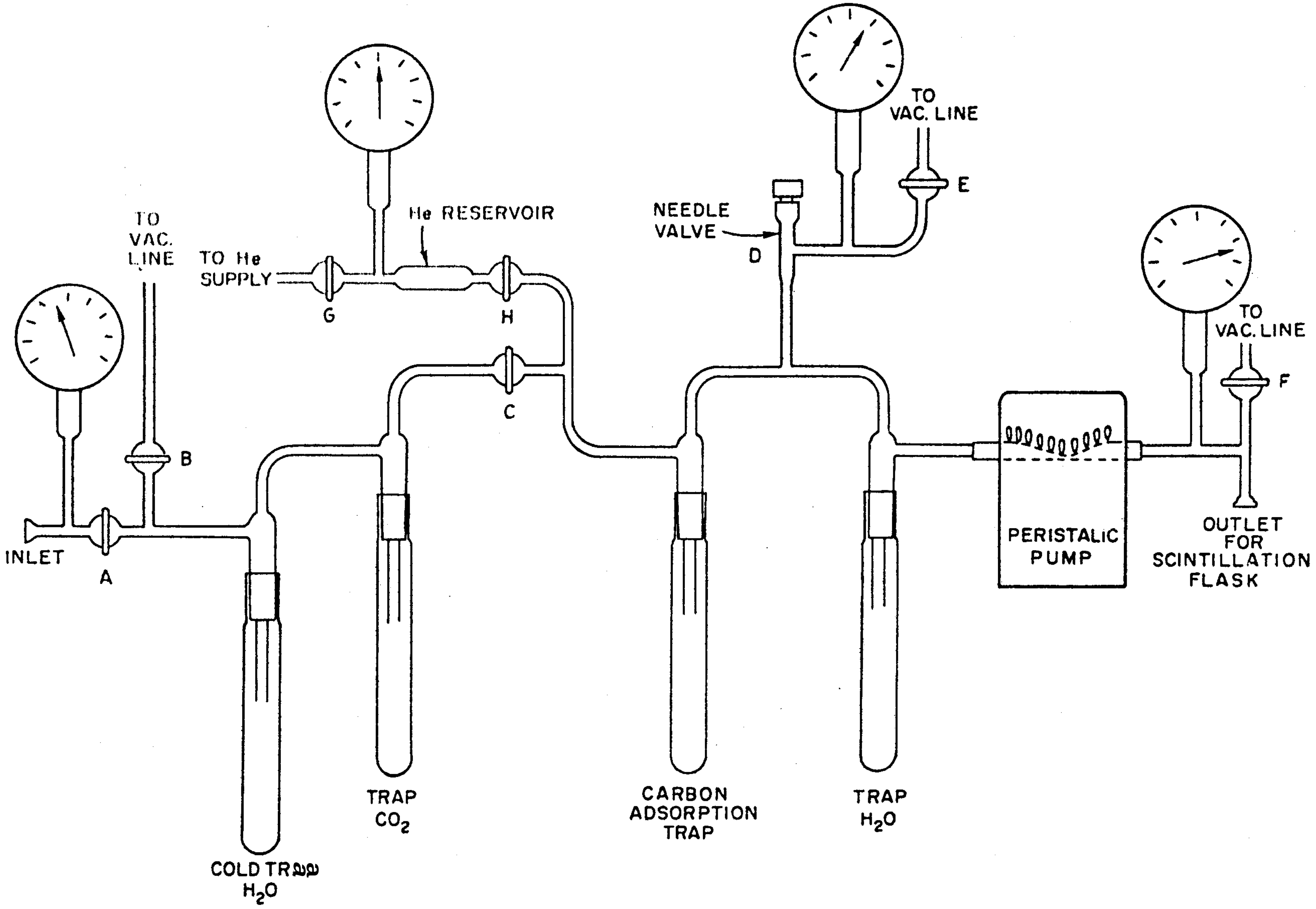

Figure 7. Radon Extraction System

The desorbed radon is transfered into a scintillation detector flask, evacuated through stopcock F, by the peristalic pump. This pump functions by positive displacement, squeezing shut a heavy walled gum rubber tubing in a wave-like motion, which drives through successive small volumes of gas. When the pressure in the carbon trap is reduced to about 10 mm Hg (about 1.5 minutes), measured by the pressure gage between D and E, pumping is stopped and another aliquot of He counting gas is introduced from the reservoir. After temperature equilibration (about 1 minute), the aliquot is again pumped into the counting flask. Four aliquots of helium are used to bring the pressure in the scintillation counter flask to just below 1 atmosphere, measured by the gage nearest the outlet. Each flush removes about 70 per cent of the He counting gas remaining in the adsorption trap-final water vapor trap portion of the extraction system, so that about 99 per cent of the radon is transfered into the outlet side of the system. Because some gas remains in the tubing between the pump and the scintillation flask, the overall volumetric transfer efficiency of the system is about 91 per cent.

Detection System--The detection system shown in Fig. 8 consists of a scintillation detector optically coupled to a photomultiplier tube in a light-tight housing. The detector is a Lucas scintillation flask in which alpha particles produce light pulses in the ZnS phosphor coated on the inside of its cylindrical surface. Light pulses pass through the quartz window forming the bottom of the scintillation flask. The window is coated with tin oxide to maintain electrical conductivity with the metal walls of the flask and prevent the radon daughter ions from migrating in any preferential direction. This detector provides a counting efficiency of about 89 per cent.

The photomultiplier (PMT) is a low noise, RCA 8053 2-inch tube with S-11 spectral respcnse. A tube socket containing a voltage divider circuit and gain and focus controls provides the interface between the PMT and the external electronic components. The housing is baffled to exclude external light during measurement. A high voltage interlock

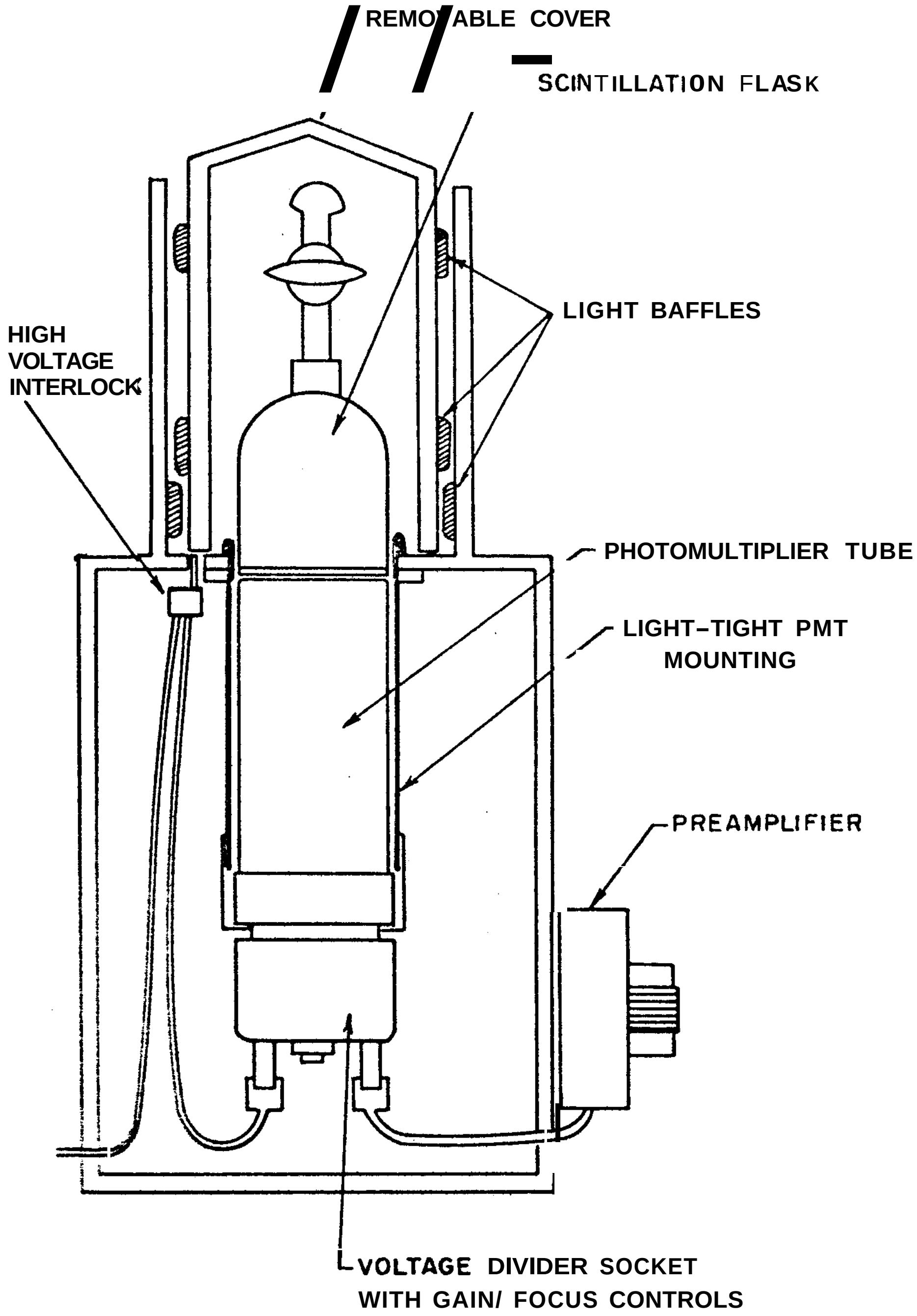

Figure 8. Radon Detection System, Cutaway View

prevents accidental damage to the PMT should the light cover be removed when the system is operating.

Other components include a preamplifier, a single-channel pulse-height analyzer with timer, and a high-voltage power supply. The preamplifier, mounted on the PMT housing, is a Hewlett-Packard 55548 set for 30 mV/pC charge sensitivity and a voltage gain of 8. This amplifies and shapes the signal for input to the Hewlett-Packard 5201L Scaler-Timer that incorporates a single channel pulse-height analyzer and a digital timer. The pulse height analyzer with a range of 5.0 volts is operated in an integral mode with a threshold set to discriminate against random thermal and electrical noise pulses.

The high voltage is supplied by a Hewlett-Packard 5551A High Voltage Power Supply which provides a very stable and well filtered voltage for the PMT.

<u>Calibration and Testing</u>--The performance of the system was evaluated by absolute calibration with a known standard, testing its stability with reference to a counting standard, and measuring the background level.

Preparation of Standards and Calibration--Standards were prepared from a National Bureau of Standards (NBS) radioactivity standard consisting of a solution of radium in acidified $BaCl_2$ carrier. The NBS standard was certified to contain $8.069 \times 10^{-10}$ (±1.00%) g $^{226}Ra$ as of March 1968. The carrier solution is 0.2 weight per cent $BaCl_2$ in a 4.5 weight per cent solution of $HCl$ certified to be 20.509 ± 0.012 g. These data represent a specific activity of 39.74 (±1.002%) pCi/ml. Aliquots of the NBS **standard** were used to prepare an absolute emanation standard and a detector stability standard.

The emanation standard was prepared by adding a 2 ml aliquot of the KBS standard to 600 ml of a 0.1 M $HCl$ solution in a 1000 ml Erylenmeyer ***flask,*** The maximum transfer error was estimated to be k1.5 per cent. Therefore, **the** emanation standard was taken to have a total activity for calibration purposes of 79.48 (±1.8%) pCi, equivalent to 176.4 (±1.8%) dpm $^{226}Ra$. The flask was fitted with a gas diffuser connected to a double stopcock assembly. Carrier gas is buhbled through the solution to remove the radon. The amount of radon grown in solution at a given time after a previous stripping is computed from equation 5. The standard was used frequently to determine the overall extraction-counting efficiency of the system.

The removal of radon from the emanation flask is known to be independent of shape, flow rate, bubble size, or acid concentration (Lucas, 1964). But the fraction of gas removed is dependent on the ratio of flushing gas and solution volume according to the relation:

$$F = 1 - 0.5^{(V_g/2V_1)} \tag{18}$$

where $V_g$ is the volume of gas bubbled through the solution and $V_1$ is the liquid volume (Lucas, 1964). For calibration tests the emanation standard was flushed with 15 1 He with an assumed radon removal efficiency of 0.99983.

The average system efficiency, including both transfer and counting efficiencies, was 0.800 (±2.5%) from the calibration of the four scintillation flasks used in this work. This value agrees well with the product of the expected volumetric transfer efficiency of 0.91 and the theoretical counting efficiency of 0.887 computed from the work of Lucas (1964). The variation between individual flasks was nearly identical to the variation between successive calibrations of each flask; therefore a single efficiency factor was used. The overall efficiency factor of the detection system, including the uncertainty of the emanation standard was 0.800 (±3.0%). This value was used with the theoretical radon daughter growth factor (tabulated in the appendix) to compute the radon activity in a sample from the count rate measured at the time after radon transfer to the scintiallation flask. To minimize uncertainty in the growth factor, counting was generally done at least one hour after transfer of the sample. The data reduction calculation is described in the appendix.

The stability of the counting system was monitored by the use of mounted standard prepared by coprecipitating the radium from an aliquot of the NBS standard with $BaSO_4$. The precipitate was slurried with activated ZnS phosphor and filtered onto a Millipore filter based on procedure 13 of Kirby (1964). The filter disc was sealed in a cylindrical lucite holder to facilitate placement on the photomultiplier tube, The counting rate of this standard divided by the theoretical daughter growth factor for a radium parent (see appendix) should yield a constant value if the counting system is stable with respect to time. For the standard operating settings of the counting equipment the value is 116.8 (±1.3%) cpm. Measured values during the project were within the expected standard deviation based on total counts.

Counting System Operation--The operating settings of the counting equipment were determined by standard procedures. The high voltage was determined from the plateau obtained by relation of counting rate of the standard with voltage. The threshold setting was determined by the relation of counting efficiency with threshold which in turn influences the discrimination against electronic noise. All three factors must be considered interactively.

The high voltage plateau for threshold settings in the range finally selected has its knee at about 850 volts. With increasing voltage, the plateau has a slope of 2.5 per cent per 100 volt increment to about 1050 volts. For this study the operating voltage was set at 900 volts.

A threshold setting above 0.2 volt was found to completely eliminate electronic noise, i.e. no observed counts in 1000 minutes. At a high voltage of 900 volts, the threshold does not affect counting efficiency for settings up to 0.3 volt; thereafter the efficiency declines by about 1.7 per cent for 0.1 increments in the setting. Therefore, the operating point was selected at 3.3 volt.

System Background--The overall system background includes three components: the background of the counting flasks; radon produced from radium in the glass, carbon, and absorbing compounds of the extraction system; and radon in the He carrier gas due to radium in the steel pressure cylinder.

The counting flasks have a background that slowly increases as a result of the deposition of 22-year $^{210}Pb$ which decays through $^{210}Bi$ to 138-day $^{210}Po$. The alpha decay of $^{210}Po$ is related to the amount of radon that decays in the scintillation flask. If a radon sample with a counting rate of 2000 cpm is in a flask for 4 hours, it will ultimately increase the background of the flask by about 0.01 cpm. The background of each flask was monitored regularly with 1000 minute counts to provide current background values. After decay of the short-lived daughter products the activity of the flasks was *40* to 70 counts in 1000 minutes when received from the manufacturer, corresponding to backgrounds of *0.04* *(516%)* to *0.07* (512%) cpm, The backgrounds increased during usage to levels of 70 to 130 counts/1000 min or 0.07 *(512%)* to 0.13 *(59%)* cpm.

The charcoal contained residual radium which produced about 0.5 pCi radon at secular equilibrium. For this reason, the charcoal trap was heated and purged prior to each experimental run. With this procedure, the system blank was found to be undistinguishable from the flask backgrounds for 1000 minute counts using the criteria for detection limit $L_D$ given by Currie (1968):

$$L_D = 2.71 + 4.65\sqrt{\mu_B} \qquad (19)$$

where $\mu_B$ is the background for the time period of interest.

The radon content in each full 240-$ft^3$ cylinder of He was determined to be about 0.001 (±30%) pCi/1. The concentration increases proportionately as He is resoved from the cylinder; therefore He cylinders were replaced **wheri** the content decreased to 50 $ft^3$. The contribution of He carrier gas to the system blank is negligible because only about 0.1 liter is used for the four standard flushes of the trap. When large volumes of He were used to strip liquid samples, the contribution was checked for significance and a correction was made when necessary.

Another contribution to background resulted from residual radium in the steel pressure cylinders used for sample collection. The carbon steel cylinders have an emanating power of 1.24 *(525%)* pCi based on measurements of four of the smaller carbon steel cylinders. Corrections to low level samples were made when necessary. The larger stainless steel tanks, used for collecting air samples, had an emanating power less than 0.1 pCi.

## Sample Measurement and Handling

Several procedures were developed for the handling of the vari us types of the sample. Specific methods were developed for gas, steam condensate, liquid, and Ra-emanation samples.

Gas Samples--Samples containing gases only, such as air and soil gas, are easiest to process. The volume of gas analyzed in the extraction system is measured by the change in gas pressure in the container before and after extraction. The total pressure in the sample container is first measured with a mercury manometer. After a portion of the gas sample is drawn through the extraction system, the pressure of the gas remaining in the container is again measured. The volume of the sample analyzed is computed by the ideal gas law using the change in pressure, and the known container volume and temperature. The radon concentration is computed from the measured activity and the volume of gas analyzed.

Condensate Samples--Samples from steam wells include condensed steam and non-condensable gases. The total non-condensable gas volume is estimated by measuring the pressure in the cylinder at laboratory temperature and subtracting the vapor pressure of water for that temperature. The volume of noc-condensable gases at standard temperature and pressure (STP) is computed from the ideal gas law. In some cases it was necessary to consider dissolved $CO_2$. Since all steam well samples were somewhat acid (measured pH ~5), probably from formation of $SO_4^{--}$ from $H_2S$ oxidation and reaction with iron oxides inside the cylinder, it was assumed that all dissolved $CO_2$ was in the carbonic acid form. A correction factor of 0.093 $cm^3$ (STP) dissolved $CO_2$ per 100 ml water was used for each 1 mm partial pressure of $CO_2$ in equilibrium with the solution. The factor comes directly from Henry's law with suitable unit!; conversion factors.

Analysis of the non-condensable gases for $CO_2$, $O_2$, $N_2$, $CH_4$, and $H_2$ was determined by gas chromatography. A Fisher Model 25 V Gas Partitioner in which He is used as a carrier gas for $CO_2$, $O_2$, $N_2$, $CH_4$, and CO separation; and argon for $H_2$. The instrument has double column separation and thermal conductivity detectors. The output signal drives a potentiometric recorder. A 0.5 $cm^3$ aliquot of the non-condensable gases was extracted from the sample cylinder into a syringe by the peristalic pump and a short section of heavy wall tubing and a valve arrangement which eliminated air contamination. The instrument was calibrated periodically with composite standards. Reproducibility of the measurements was about ±10 per cent. Significant instrumental instability due to a recorder malfunction occurred during one period of measurements.

After analysis of the non-condensable gas, He carrier gas was introduced through the bottom of the cylinder to strip any dissolved radon in the condensed water and to bring the total gas pressure in the cylinder to about 1 atmosphere. The condensate was immediately drained from the tank into a graduated cylinder to measure its volume.

From this point the sample was handled as described in the section on gas samples. Radon concentrations may be computed in relation to gases or condensate.

Liquid Samples--If the sample contained more than about 300 ml (about 6% of the cylinder volume) a more thorough stripping procedure was required. The non-condensable gases were measured as described for condensate samples. Then He carrier gas was bubbled through the liquid in sufficient volume to insure complete radon removal. The carrier gas was accumulated in a previously evacuated large transfer tank. The carrier gas was then drawn into the extraction system from the transfer tank according to the procedure for gas samples, and the fraction analyzed was determined by pressure difference measurement.

Radium Emanation Samples--The dissolved radium content of liquids or the emanating power of solids was determined by a procedure identical to that used for the calibration standard. The liquid sample, or a rock sample immersed in distilled water, was placed in a flask with a diffuser, stripped with He to remove radon, and sealed. After a period of about a week, the radon in the sample was flushed into the extraction system and the equilibrium amount of radium or radium emanating power calculated from the radon activity and the growth relation for the radon and radon daughters from a radium parent.

## Sample Collection Methods

Standard procedures were established for sampling of wells, ambient air, and soil gas.

Geothermal Well Samples--Wells may produce dry or slightly superheated steam, pressurized liquid, or a steam-water mixture, Several sampling techniques are possible (see e.g. Mahon, 1964; Finlayson, 1970; Ellis, et al., 1968). In this study samples were drawn directly into evacuated cylinders connected to the wellhead. This method is a modification of the method used for collecting steam samples from a separator (Mahon, 1964). The method was used to obtain samples from dry steam and pressurized liquid wells, and samples from a separator.

The sampling configuration is illustrated in Figure 9. The 4.7-liter evacuated steel cylinder and a ¼ inch stainless steel tube is connected by suitable couplings to a tap on the wellhead, A "T" fitting with a valve and bleed line permits purging of the connecting line and fittings by flowing steam or liquid for a period of at least 2 to 5 minutes. The valve on the bleed line is closed and the cylinder valve is immediately opened, allowing fluid to flow into the tank until pressure equilibrium is established. One minute was allowed. Some condensation may occur in steam well sampling due to heat transfer from the tank to the air.

Two variations of the method were tried and rejected. One involved opening valves on both ends of the cylinder to permit steam or liquid flashing to steam to flow through. For both steam and liquid wells,

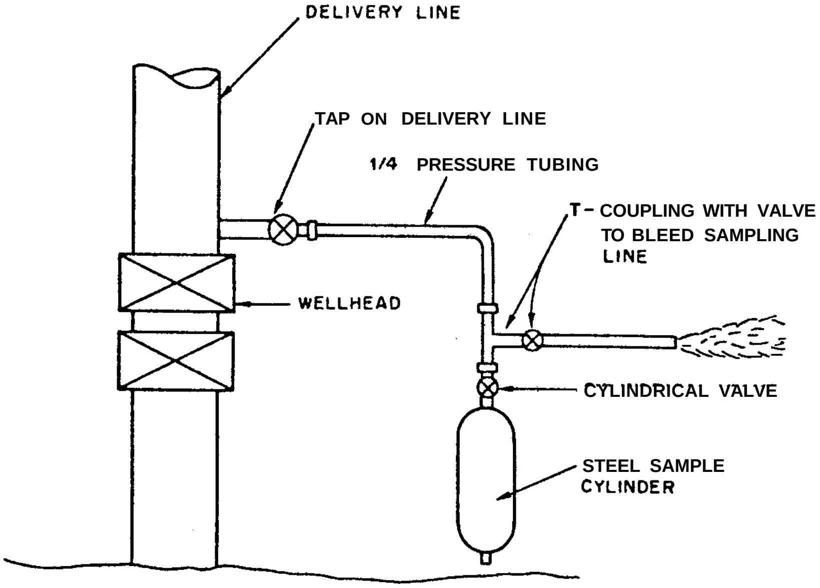

Figure 9. **Well Sampling Configuration.**

reduced radon-water ratios were noted. For the dry steam case the major effect was probably the condensation of steam on the tank walls while radon and non-condensables flowed through with the remaining steam. For the liquid well case, the flashing liquid may have stripped radon and other non-condensables from the contained liquid.

The second variation involved cooling the cylinder externally with water to induce increased condensation for a larger sample. The results were erratic. In one case this variation appeared to work satisfactorily, but in another case a reduced ratio of radon and non-condensables to water was noted. The latter case might be explained by the condensed water taking up a large enough fraction of the cylinder (about 25%) to displace some of the non-condensable gases. Because of these uncertainties, and the great sensitivity of radon measurement in smaller volumes, the method was not employed in further collections. However, the data for both of these variations are included in this report.

Ambient Air Samples--Air samples were taken in 34.4 liter evacuated stainless steel cylinders at approximately 1 meter above ground. Contamination by radon from breath was avoided.

Soil Gas Flux Samples--Soil gas flux samples were taken by the accumulator method (e.g., Wilkening, et al., 1972). A circular hoop about 56 cm in diameter and 15 cm high is driven about 10 cm into the ground. A steel cylinder, half of a 55-gallon drum, is placed over the hoop. A pressure equalizing orifice and a valve-connector fitting are mounted through the top. A tube extends about half-way down into the drum from the valve. Samples are drawn into evacuated cylinders at intervals of one to two hours. The increase in radon concentration is related to the radon flux by

$$J = h \frac{\Delta C}{\Delta t} \qquad (20)$$

where h is the height of the accumulator, 44 cm, and $\frac{\Delta C}{\Delta t}$ is the rate of increase of radon concentration.

# CHAPTER 4

## RESULTS

### Sampling Program

Radon samples were taken of geofluids from 16 wells, from ambient air in the environs of some of the wells, and in the flux of gas emanating from soil in and near one well field. The samples were obtained during the 7-month period from November 1973 through May 1974.

Thirteen of the wells were in the vapor-dominated fields of The Geysers area in northern California. Nine of these wells were production wells delivering steam to operating power plants and four were in a field being developed for future use. Permission to sample these wells was given by the Burmah Oil and Gas Company and the Union Oil Company of California. Well data and production parameters--flow rates, pressures, and temperatures--were supplied for the sampling periods by respective company personnel.

The other three wells were located in the hot brine liquid-dominated systems of the Imperial Valley of southern California. Two of the wells were in the East Mesa KGRA operated by the U.S. Bureau of Reclamation to study the feasibility of desalinating water with geothermal energy. The third well was in the Salton Sea KGRA where the San Diego Gas and Electric Company is studying the feasibility of electric power generation. Well data and production parameters were supplied for the sampling periods by field personnel.

### Presentation of Data

Well Identification--Since production information for wells in the privately-held fields of The Geysers area is proprietary, those wells are identified in this report by an arbitrary numbering system. The identification consists of a Roman numeral signifying a particular group of wells, and a letter signifying the individual well in the group. Groups I through III include the production wells and group IV includes the developmental wells.

Errors in Measurement--Estimated errors in measurement in this report are uniformly reported as a standard deviation. The estimates of probable error for measured quantities were based on the following considerations:

Radioactivity--The standard deviation of radioactivity measurement is given by Poisson statistics as the square root of the total number of counts recorded in a given measurement. Since most of the radioactivity measurements were made of at least 1000 counts, the standard deviation was of the order of ±3.0% or less.

Pressure Measurements--Pressure measurements involved reading the height of mercury in the two arms of a manometer. The estimated accuracy of the difference between the two values was ±2 mm.

Water Vapor Pressure--Water vapor pressure in sample tanks was found from standard tables using measured laboratory temperature as the parameter. Temperatures were estimated to be within ±0.4 °C which led to probable errors in vapor pressures of about *0.4* mm.

Non-Condensable Gases Volumetric Fractions--Measurements of gas composition made with the gas partitioner were of varying and unpredictable accuracy. Calibrations made with known-composition samples (prepared from standard laboratory grade compressed gases) varied about ±5% for replicate samples of the same standard and about ±10% for standards of different composition. Some of the difficulty is attributable to the need to use two different carrier gases (argon for $H_2$ snd helium for $CO_2$, $O_2$, $N_2$ and $CH_4$) with two separate sample injections to measure the five gases of interest. Some difficulties were traceable to equipment problems with injection, and, on one occasion, to erratic electronic malfunction of the recorder attached to the gas partitioner. Even when there were no obvious equipment difficulties, there was no consistent error for either carrier gas; total percentages for all 5 gases even in known-composition standards varied from 100% by an average of about 10%. In unknowns, the total often differed from 100% by larger values. In using volumetric fractions of noncondensable gases for computation, the estimated error was taken to be the larger of 10% or the difference between the measured total and 100%. However, because of the poor experience with the gas analyzer, these estimates are considered to be the smallest likely estimate of error.

Condensate Volume--The error in the volume of liquid condensate extracted from sample cylinders allowing for a small amount of retention and the reading error of standard graduated cylinders was estimated to be ±2%.

Transfer and Counting System Efficiency-The overall efficiency of the transfer and counting system was considered to be ±3% based on actual calibration measurements and the estimated probable error in the calibration standard as discussed in Chapter 3.

The estimated errors in measured quantities were combined according to the rules for propagating errors (see example data reduction in the Appendix). The computed quantities included estimates of error according to the following schemes:

Radon Content of Sample--includes counting error, calibration efficiency error, and error in sample fraction based on pressure measurements. The measurement errors in the sample radon content ranged from about ±3.0% to ±4.0%.

Volume of Non-Condensable Gases--includes pressure measurement error, and error in water vapor pressure, and was generally ±15 to 20 $cm^3$. This error is often proportionally large, up to ±100% or more, for samples where the amount of non-condensable gas in the sample is small. The large uncertainties resulted when the total pressure measured in a sample cylinder was only a few millimeters greater than the vapor pressure of the water. Subraction of the estimated water vapor pressure from the total pressure (each with an associated uncertainty) yielded the estimated pressure associated with the ran-condensable gases, and this difference often had a proportionally large standard deviation.

Radon Concentration in the Condensate--includes error in Radon Content of Sample and error in Volume of Condensate. The range of errors varied from about ±3.7% to ±4.2%.

Radon Concentration in $CO_2$--includes error in Volume of Non-Condensable Gases, error in Volumetric Fraction of Non-Condensable Gases, and error in

Radon Content of Sample. These errors ranged from about ±10% to ±50%. Error limits for individual measurements and computed quantities are not included in tabular presentations unless they are greater than the ranges noted in the preceding discussion.

### Evaluation of Sampling Techniques

Two basic types of sampling techniques were tried in the field: flow-through and evacuated cylinder. The results of the first test are presented in Table 8. The samples were taken from two wells in the vapor-dominated developmental field at The Geysers which were flowing at "bleeding rates." The term "bleeding" refers to the practice of venting completed wells to the atmosphere at: low flow rates to prevent excessive: buildup of non-condensable gases in the wellbore.

The flow-through samples from the steam wells exhibit a radon concentration in the condensate which is about half of that for the evacuated-cylinder samples. The smaller radon concentration in the flow-through samples is likely due to enrichment of water in the sample from condensation of steam on the cylinder walls with concurrent escape of the non-condensable gases.

A similar result was observed during subsequent field tests for sampling from brine wells. The results shown in Tables 10 and 11 indicate that flow-through samples exhibit radon concentrations in the condensate only about one-third that of evacuated cylinder samples. In this case it is likely that the escaping steam bubbling through the condensed liquid in the sample cylinder strips out the non-condensable gases including radon. Accordingly, flow-through sampling was rejected for further field work.

A variation of the evacuated-cylinder sampling technique was tried for steam well sampling. This involved inducing additional condensation by pouring water over the cylinder in an attempt to increase sample size. The results of this test are presented in Table 9. The radon in condensate concentration for the fifth sample in the series taken from well IV-C with induced condensation is about 17% lower than the average (125,000 pCi/l) of the preceding 3 samples (the first sample in the series was ignored because of the probability of inadequate time allowed to clear the wellhead tee and connecting lines). The

## Table 8

## Summary of Data

Wells IV-A and IV-B     Geysers Area     12 Novembes 1973

| | Well IV-A | | Well IV-B | |
|---|---|---|---|---|
| | Flow-Through Sample | Evacuated Tank Sample | Flow-Through Sample | Evacuated Tank Sample |
| Radon Content of Sample at Time of Collection, pCi | 395 | 3200 | 306215 | 2160 |
| Volume of Condensate, ml | 58 | 210 | 32 | 103 |
| Volume of Non-Condensable Gases, $cm^3$, ($0^\circ C$, 760 mm Hg) | 23 | 115 | 566 | 158 |
| Gas Analysis, Volume % | | | | |
| $CO_2$ | 33.1 | 29.4 | -- | |
| $CH_4$ | 8.2 | 6.0 | -- | No Gas Analysis Performed |
| $O_2$ | 1.2 | 1.1 | ∿1 | |
| $N_2$ | 7.3 | 11.7 | ∿99 | |
| $H_2$ | 43.0 | (51.8) 1/ | -- | |
| Total | 95 | (100) | ? | |
| Radon Concentration. pCi/l 2/ | | | | |
| Condensate 3/ | 6810 | 15200 | 9560±500 | 21000 |
| Non-Condensable Gas | 17100 | 27800 | -- | 13700 |
| $CO_2$ | 51700 | 95000 | -- | -- |

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1/ $H_2$ percentage assumed to total 100%

2/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

3/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

Estimate? Wellhead Condition: Flowrate 5000 lb/hr, Pressure 450-460 psig, Temperature 450°F

## Table 9
### Summary of Data

Well IV-C and IV-B  Geysers Area  17 January 1974

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time of Sample | 09:55 1/ | 10:05 1/ | 10:12 1/ | 10:18 1/ | 10:27 2/ | 10:50 2/ | 10:5[illegible] |
| Radon Content of Sample at Time of Collection, pCi | 7900 | 2300 | 28 [illegible]0 | 28 00 | 36000 | 200 | 610 |
| Volume of Condensate, ml | [illegible]1 | 26 | 26 | 28 | 270 | 10[illegible] | 21 |
| Volume of Non-Condensable Gas cm$^3$, (0°C, 760mm Hg) | 56 | [illegible]84 | [illegible] | 62 | 230 | [illegible] | 68 |
| Volume of CO$_2$, cm$^3$, (0°C, [illegible]) | 20 | 200 | [illegible]0 | [illegible]0 | 80 | 6 | 2 |
| Gas Analysis, Volume % | | | | | | | |
| CO$_2$ | 3[illegible] 3 | [illegible].4 | 3[illegible] [illegible] | [illegible] 1 | [illegible] 1 | 2.4 | 38.1 |
| CH$_4$ | 7 1 | [illegible] 6 | 7 6 | 7 [illegible] | 8.6 | [illegible].6 | 7.8 |
| O$_2$ | 0 6 | 0 2 | 0 1 | 0.[illegible] | 0 1 | [illegible] 1 | 1.3 |
| N$_2$ | [illegible] [illegible] | 3.9 | 3 [illegible] | 4 [illegible] | [illegible] 7 | [illegible].2 | 0.[illegible] |
| H$_2$ | (47.[illegible])* | 6.8 | [illegible] [illegible] | [illegible].8 | 6.2 | 2 [illegible] | 1.7 |
| Total | 100 | [illegible]8.9 | [illegible] 7 | [illegible].0 | [illegible]7 7 | [illegible] 5** | [illegible] 7** |
| Radon Concentration, pCi/liter 3/ | | | | | | | |
| Condensate 4/ | 14 600 | 124 00 | 27 [illegible] | [illegible]000 | [illegible]7000 | 4100 | 2300 |
| Non-Condensable Gas | [illegible]940 | 60600 | 5100 | 5[illegible]00 | [illegible]000 | 79 [illegible]0 | 27[illegible] |
| CO$_2$ | [illegible]6000 | [illegible]0000 | 4 800 | [illegible]2000 | 69000 | 58000 | [illegible] |

* H$_2$ percentage assumed to total 100%

** Uncertain analysis, some H$_2$S present but not analyzed

1/ Samples taken in evacuated bottles cooled by ambient air

2/ Samples taken in evacuated bottles cooled by water poured on tank surface

3/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

4/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

## Table 10

### Summary of Data

Bureau of Reclamation Well Mesa 6-2 East Mesa KGRA 30 November 1973

| Time of Sample | 12:07 | 12:15 | 12:23 |
|---|---|---|---|
| Radon Content of Sample at Time of Analysis, pCi/liter | 6.4±0.5 | 1.1±0.1 | 8.1±0.4 |
| Radon in Equilibrium with Dissolved Radium, pCi/liter | 0.65±0.05 | 0.27±0.03 | 0.46±0.06 |
| Excess Radon at Time of Analysis, pCi/liter | 5.8 | 0.85 | 7.64 |
| Estimated* Excess Radon at Time of Sampling, pCi/liter | 9.9 | 9.3 | 15.5 |
| Estimated* Total Radon at Time of Sampling, pCi/liter | 10.5±0.8 | 9.6±0.5 | 16.0±0.8 |
| Total Dissolved Solids, mg/liter | 2220 | 2190 | 2100 |

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* Estimate based on assumption that contribution of radon from dissolved radium was at equilibrium at time of sampling.

## Table 11

### Summary of Data

### Bureau of Reclamation Wells Mesa 6-1 and 6-2 East Mesa KGRA 14 February 1974

| | East Mesa 6-1 | East Mesa 6-2 | | | |
|---|---|---|---|---|---|
| Time of Sample | 11:00 | 11:45 | 12:00 | 12:15 | 12:30 2/ |
| Radon Content of Sample at Time of Collection, pCi 1/ | 288 | 140 | 156 | 157 | 65±3 |
| Radon in Equilibrium with Dissolved Radium, pCi | 123 | 0.50±0.04 | not measured | 0.70±0.08 | not measured |
| Volume of Condensate, ml | 4180 | 4240 | 4300 | 4350 | 2050 |
| Volume of Non-Condensable Gases, cm$^3$, (0°C, 760 mm Hg), in Equilibrium with Solution | 20 * | 72 | 52 | 72 | 180 |
| Total Estimated CO$_2$, cm$^3$, (0°C, 760mm Hg) | 1070 | 470 | 440 | 640 | 220 |
| Gas Analysis, Volume % | | | | | |
| CO$_2$ | 76.3 | 97.7 | 97.0 | 86.5 | 79.3 |
| 4 | 5.7 | 4.8 | 7.5 | 4.7 | 1.2 |
| O$_2$ | 0.3 | 0.3 | 0.5 | 0.4 | 0.3 |
| N$_2$ | 5.5 | 6.4 | 5.6 | 7.0 | 33.7 |
| H$_2$ | 26.5 | 8.8 | 8.6 | 17.0 | 5.0 |
| Total | 114.3 | 118.0 | 119.2 | 115.6 | 119.8 |
| Radon Concentration, pCi/liter 3/ | | | | | |
| Condensate | 68.9 | 33.0±1.5 | 36.2±1.6 | 36.0±1.6 | 31.7±1.5 |
| CO$_2$ | 1840 | 1990 | 3090 | 2520 | 460 |

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1/ Based on assumption that contribution of radon from dissolved radium was at equilibrium at time of sampling

2/ The 12:30 sample taken in 30 seconds, all others in 60 seconds.

3/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

sample from well IV-B (Table 9) taken with induced condensation is about 3% lower then the sample taken without induced condensation. These results suggest that limited induced condensation will not materially affect sample composition with respect. to radon in condensate concentration. The induced condensation samples from wells IV-B and IV-C had about 6% and 27% respectively of the cylinder volumes occupied by liquid. The implication is that as the condensate volume increases there may be a displacement on non-condensable gases back into the sampling line with a consequent enrichment of water content of the sample. For sake of consistency, it was decided to abandon the induced-condensation technique for further sampling.

Indications of both short- and long-term consistency of radon to condensate concentrations are inferrable from the results in Tables 8 through 11. Short-term consistency in the evacuated-cylinder sampling technique (where cylinders are opened to the sampling line for 60 seconds and cooled only by ambient air) is shown in the second through fourth samples taken on 17 January 1974 from steam well IV-C (Table 9) and the first through third samples taken on 14 February 1974 from brine well Mesa 6-2 (Table 11). These results are also shown in Figure 10. The three steam well samples agree completely within standard deviations; and of the three brine well samples, two agree within the standard deviation and the other is within 6% of the average (35.07 pCi/1) of the three samples taken under identical conditions, while the standard deviation of radon to condensate concentrations for individual samples is between 4 and 5%. The consistency of these short-term samples depends on both the consistency of the sampling technique and the consistency of the fluid composition over the time intervals involved. Because of the low flow rates (only a few percent of maximum possible) involved in both the steam and brine well samples, it may be assumed that the fluid composition is constant. Therefore, it may be inferred that the evacuated-cylinder sampling technique yields reproducible results for radon to condensate concentrations within the estimated standard deviations.

At these low flow rates, the individual radon to $CO_2$ concentrations

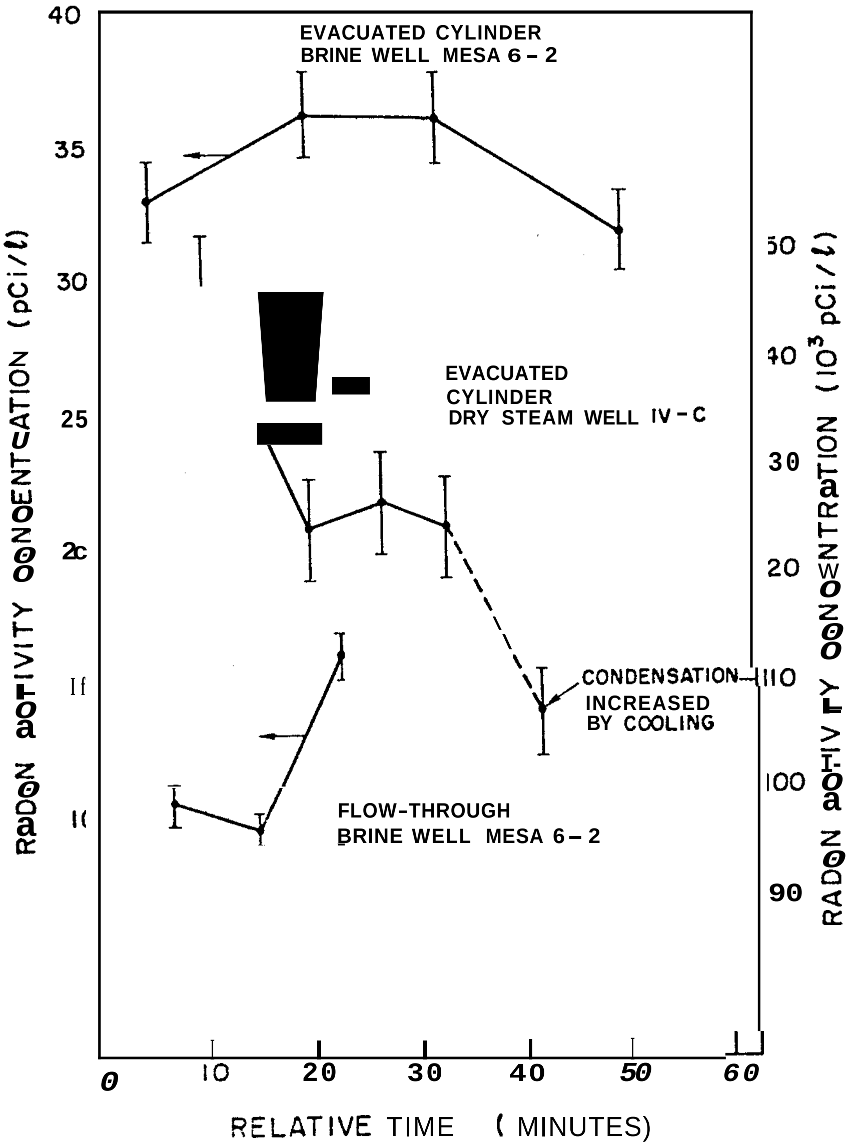

Figure 10. Short term variability of radon concentration* in liquid and dry steam wells.

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* Apparent concentration: ratio of radon activity to condensate or gas collected in sample; divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure.

are also within one standard deviation of the respective means of the two series of three measurements considered. This tends to confirm the inference of consistency of the sampling technique given the assumption of constant fluid composition. It should be noted that the relative variation of the radon concentration in $CO_2$ is much larger than the variation of the radon concentration in the condensate because of the large error in the non-condensable gas volumetric fraction analysis.

Longer-term stability for well IV-B is indicated by the evacuated-cylinder samples of 12 November 1973 (Table 8) and 17 January 1974 (Table 9). The 12 November sample shows a radon-condensate concentration that is 13% lower than the 17 January sample. The standard deviations for the two measurements are about 4 and 5% respectively. The difference can be attributed in part to a change in wellhead fluid composition. (The most likely reason for the change in wellhead fluid composition is a difference in the "bleeding" rate in November and January. It was observed in later tests that at bleeding rates the wellhead fluid is enriched in non-condensable gases because of condensation of steam in the wellbore, and that this enrichment is strongly dependent on the bleeding rate.)

In summary, the evacuated-cylinder sampling technique adopted for all further field collections appears to provide reproducible results within expected standard deviation limits for both steam and brine well samples under conditions where wellhead fluid composition can be assumed constant. The flow-through technique was rejected on the basis that it permitted an unpredictable water enrichment in the sample. The induced-condensation may offer an alternative for increasing sample size, but the limits of condensation allowable without resulting in water enrichment would have to be established by further testing.

## Sampling of Wells in Vapor Dominated Systems

Geothermal steam wells flowing at high rates (>50,000 lb/hr) were sampled under two conditions: 1) during well performance testing and, 2) during production of steam for power generation. The well performance tests consisted of pressure drawdown runs in which a well is started from "shut-in" (bleeding) condition and allowed to flow for a period of 6 to 10 hours and then shut-in again. Measurements of pressure decline and flow rate during flow, and pressure buildup after flow is stopped, are used to evaluate steam deliverability and reservoir characteristics by standard reservoir engineering methods (e.g., Matthews and Russell, 1967). Two wells in the developmental area of The Geysers were sampled during the pressure drawdown phase of production testing. A series of three drawdowns for each of the two wells was sampled. Radon concentration measurements during these drawdown tests were evaluated to determine possible dependence of concentration on flow rate.

The production wells were sampled while they were producing steam for delivery to electric generating stations at The Geysers. These wells had been flowing at approximately constant rates for long periods--several weeks or more--prior to sampling. Two of the wells were sampled periodically during a 24-hour period; one of the wells flowed at a nearly uniform rate, the second at three different rates. Radon concentrations in samples from the second well were evaluated to determine possible flow-rate dependence. Single samples were taken from seven other production wells. Radon concentrations in these samples were evaluated to determine the general range of radon levels in different wells and possible relations of radon concentrations to well groups or depth.

Measurement during Performance Testing--The first radon measurements during performance testing were made on samples taken from well IV-C, which reaches a total depth of 7134 ft in the Franciscan graywacke of the Geysers area. The wellhead elevation is 2480 ft; the casing extends to a depth of 2556 ft and the hole is open below that level to the bottom.

Drawdown runs were made on successive days, 1 and 2 February, 1974, and a third about 5 weeks later on 10 March, 1974. The data are presented in Table 12. The radon-condensate concentration and steam flowrates are shown in Figure 11.

Two general results are noted: 1) radon-condensate concentrations and the ratios of noc-condensable gas volume to condensate volume are

## Table 12

### Summary of Data

W 1 IV C    Geysers Area    1 [illegible] 1974

[illegible] Dra down Test 1/

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time of Sample | [illegible] 17 2/ | 10 25 2/ | 10 35 2/ | 12 0 | 13 [illegible] | 14 [illegible] | [illegible] |
| Radon Content of Sample at Time of Collection, pCi | 2000 | 9000 | 9000 | 640 | [illegible]0 | 70 | 80 |
| Volume of Condensate, ml | 115 | 73 | 66 | 11 | 12 | [illegible]9 | 16 |
| Volume of Non-Condensable Gases cm$^3$, (0°C, 760mm Hg) | 2 30 | [illegible]90 | 34 6 | [illegible] | 3 | 8 | [illegible] |
| Volume of CO$_2$, cm$^3$, (0°C 760 mm Hg) | 12 0 | 360 | 100 | 7.9 | 6 0 | 9 [illegible] | 7.9 |
| Gas Analysis, Volume % | | | | | | | |
| CO$_2$ | [illegible] 5 | [illegible]1.0 | [illegible] 8 | [illegible] 5 | [illegible] 5 | [illegible].0 | [illegible] 5 |
| CH$_4$ | 9 1 | 7.4 | 9 2 | 6 6 | 9 3 | 10 6 | 8.0 |
| O$_2$ | 0 3 | 8.9 | 0 2 | 0.8 | 1 2 | 2 2 | 1 7 |
| N$_2$ | 3 6 | [illegible].0 | 2 7 | [illegible].0 | [illegible] 2 | 21 5 | 2 2 |
| H$_2$ | 41 5 | [illegible] 5 | [illegible].0 | ? | [illegible] 5 | [illegible] 5 | [illegible] 5 |
| Total | [illegible]5 0 | [illegible]6.8 | 105 9 | ? | 105 [illegible] | 10 5 | [illegible]8 9 |
| Radon Concentration, pCi/liter 3/ | | | | | | | |
| Condensate 4/ | 110x10$^4$ | (64±3.4)x10$^4$ | 58x10$^4$ | .49x10$^4$ | .35x10$^4$ | .47x10$^4$ | .43x10$^4$ |
| Non-Condensable Gas | 5000 | 2000 | 8000 | 2000 | 3000 | 9000 | 2000 |
| CO$_2$ | [illegible]0000 | 3000 | 6000 | 800 0±4 [illegible]00 | [illegible]00 0± 2000 | 200 0± 8000 | 9000±[illegible]7 [illegible]0 |

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1/ Test flow started at 11:35

2/ Samples taken at bleeding rate, approximately 5000 lb/hr

3/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

4/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

## Table 12 (continued)

## Summary of Data

Well IV-C Geysers Area 2 February 1974

Sampled during Pressure Drawdown Test[1]

| Time of Sample | 10:20 | 11:30 | 12:[illegible]5 | 13:25 | [illegible] |
|---|---|---|---|---|---|
| Radon Content of Sample at Time of Collection, pCi | 2380 | 123[illegible] | 7[illegible]0 | 800 | 580 |
| Volume of Condensate, ml | 16[illegible] | 161 | 1[illegible]0 | 158 | 13[illegible] |
| Volume of Non-Condensable Gases, $cm^3$, ($0^oC$, 760mm Hg) | 54 | 190 | 45 | 22 | [illegible] |
| Volume of $CO_2$, $cm^3$, ($0^oC$, 760mm Hg) | [illegible]2 | 15 | 10 | 10 | [illegible] 2 |
| Gas Analysis, Volume % | | | | | |
| $CO_2$ | 40.5 | 8.1 | 22.0 | 46.5 | 44.5 |
| 4 | 9.4 | 1.7 | 4.4 | 10.3 | 11.8 |
| $O_2$ | 0.3 | 9.5 | 7.5 | 0.6 | 0.8 |
| $N_2$ | 4.0 | 81.0 | 36.0 | 8.4 | 8.0 |
| $H_2$ | 53.0 | 3.0 | 31.5 | 42.0 | 40.0 |
| Total | 107.2 | 103.3 | 101.4 | 107.2 | 105.3 |
| Radon Concentration, pCi/1[2] | | | | | |
| Condensate[3] | 14[illegible]00 | [illegible]00 | 5[illegible]00 | 5100 | 4300 |
| Non-Condensable Gas | 44000 | 6300 | 17000 | 36000 | 116000 |
| $CO_2$ | 111000 | 78000 | 77000 | 78000±57000 | 2[illegible]0000±780000 |

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1/ Test flow started at 10:15

2/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

3/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

### Table 12 (continued)

Summary of Data

Well IV-C   Geysers Area   10 March 1974

Sampled during Pressure Drawdown Test[1]

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Time of Sample | 07 25[2] | 0[illegible] 6 | 0[illegible] 33 | 0 5 | 1 3 | 4 0 | 5 0 | 6 45 | [illegible] 30 |
| Radon Content of Sample at Time of Collection, pCi | 1000 | 7[illegible] | [illegible]2 | [illegible]7 | [illegible] 3 | [illegible]8 | 4 [illegible] | [illegible] 5 | [illegible]2 |
| Volume of Condensate ml | 20 | 16 | 1[illegible] | 12 | [illegible]3 | [illegible]7 | 2 1 | 1 | 1 8 |
| Volume of Non-Condensable Gases cm³, (0°C, 760mm Hg) | 9[illegible] | 8 | [illegible]9 | 6 | 2 | 1±16 | 16±6 | 18 | [illegible] |
| Volume of $CO_2$, cm³, (0°C, 760mm Hg) | 11 | 3.7 | 12 | 0.4 | 8 | 2 | 1 | 4 | 3 |
| Gas Analysis, Volume % [3] | | | | | | | | | |
| $CO_2$ | 1 1 | [illegible] 8 | 4 5 | 2.5 | 3.4 | [illegible] 5 | [illegible] 2 | 23.2 | [illegible] 0 |
| $CH_4$ | 1.4 | [illegible] 9 | 7.0 | [illegible] 1 | 5 [illegible] | [illegible] 5 | 7 7 | 1 | 1 5 |
| $O_2$ | 1.3 | 1 3 | 0.4 | [illegible] 5 | 1.0 | 5.4 | 3 1 | 2 2 | 1 3 |
| $N_2$ | 7.4 | 8 3 | [illegible].4 | [illegible].8 | 2 3 | [illegible] 6 | 7 5 | 1 [illegible] | 7[illegible] [illegible] |
| $H_2$[4] | [illegible].8 | [illegible] 7 | 0 7 | [illegible] 1 | [illegible].4 | [illegible].0 | [illegible] 5 | [illegible] 2 | [illegible] 5 |
| Radon Concentration pCi/liter[5] | | | | | | | | | |
| Condensate[6] | [illegible] 00 | 6[illegible]0 | [illegible] 30 | [illegible] 30 | [illegible]00 | 38[illegible] | 3[illegible]6 | [illegible]20 | [illegible] 9 |
| $CO_2$ | $100\times10^4$ | $(20\pm17)\times10^4$ | $(5.2\pm2.7)\times10^4$ | $120\times10^4$ | $(5.6\pm4.2)\times10^4$ | $(20\pm27)\times10^4$ | $(36\pm36)\times10^4$ | $(11\pm10)\times10^4$ | $18\times10^4$ |

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1/ Test flow started at 7:35

2/ Sample taken at bleeding rate, approximately 5000 lb/m

3/ Gas analyzer considered unstable for this series of samples

4/ Values assumed as balance to total 100%

5/ Apparent concentration: ratio of radioactivity to condensate or gas collected in sample

6/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

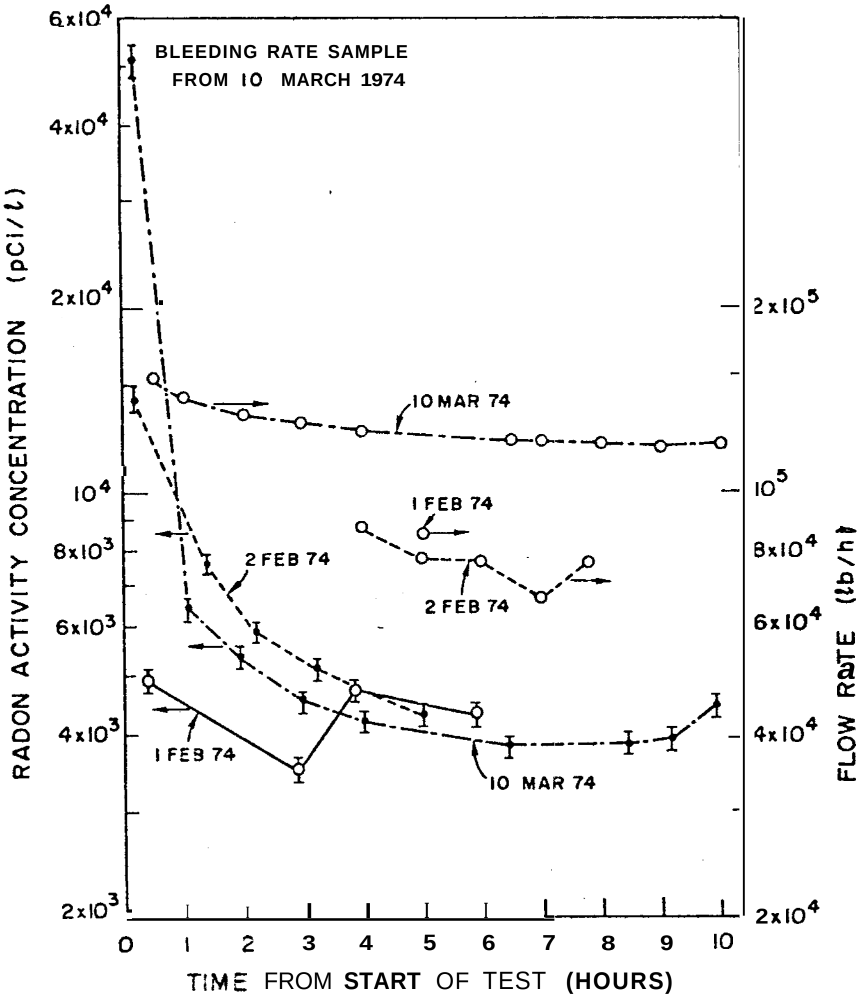

Figure 11. Radon activity concentration* and flow rate during pressure drawdown tests, Geysers Area, Well IV-C.

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* Apparent coccentration: ratio of radon activity to condensate or gas collected in sample; divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure,

larger in bleeding rate samples than in higher flow rate samples, and 2) there is an indication of an approach to a steady state value for radon-condensate concentrations after about 4 hours of test flow.

The February 1 data require special comment before proceeding with the discussion. The well had apparently built up a volume of water from steam condensation due to well-bore heat losses during the period of low bleeding rate flow prior to the drawdown test. This condition was inferred from amounts of liquid sprayed from the well during the first few hours of the drawdown run. The consequent enrichment of the fluid sampled at the wellhead is evidently reflected in the first two samples taken after the start of the drawdown. These two samples have lower values than would be expected by comparison with samples taken at similar times during the 2 February and 10 March drawdown tests (see Figure 11).

The samples taken from well IV-C at bleeding rates exhibit a variation in radon-condensate concentrations greater than one order of magnitude. The lowest value, 50,500 pCi/l, was observed on 10 March; the highest, 1,100,000 pCi/l, was observed on 1 February (see Table 12). The average for the five samples taken on 17 January was about 126,000 pCi/l. All of these bleeding rate samples have radon-condensate concentrations at least one order of magnitude larger than the average of 4100 pCi/l for the 7 samples taken 4 or more hours after the start of the three drawdown tests on well IV-C. A qualitatively similar pattern occurs for the ratio of total non-condensable gas volume to condensate volume observed in bleeding rate samples versus performance test samples (see Tables 9 and 12).

These results indicate that the condensation of steam in the wellbore due to wellbore heat losses under bleeding rate conditions can enrich the non-condensable gas content at the wellhead by roughly one to two orders of magnitude. The amount of enrichment is apparently inversely related to the bleeding rate. Qualitative observation of the bleeding [illegible] prior to the 1 February and 10 March drawdowns were that the 10 March rate was considerably greater than that for 1 February. The data in Table 12 show that the radon-condensate concentrations in the 1 February bleeding rate samples were as much as 20 times that of the 10 March bleeding rate sample.

Following the start of high flowrates for the drawdown, the radon-condensate concentrations were observed to decline during the first few hours, with an indication of a leveling off to a constant value after about *4* hours (see Figure 11). This trend is most evident in the 10 March drawdown. The 1 February data follow a different pattern at early times probably attributable to the liquid enrichment discussed above. The 1 and 2 February data do not extend for sufficient time to confirm the apparent approach to a steady state, but they are not: inconsistent. with that general trend.

The five samples taken on 10 March at four or more hours after start of test flow have an average radon-condensate concentration of *4040* pCi/l; the individual measurements differ from this average by 120 to 390 pCi/l (about 3 to 10%) and have individual estimated standard deviations of 160 to 190 pCi/l (about *4%).* The 1 February sample at about 6 hours after start of test flow had a concentration of *4300* ± *170* pCi/l as did the fifth hour sample on 2 February. These values are 260 pCi/l (about 6%) above the average for the samples at four or more hours on 10 March.

The length of time required for the radon-condensate concentrations to approach the apparent steady state level is about *4* hours for the 10 March test. During this time, many wellbore volumes of fluid were produced. It may be inferred that the enrichment of non-condensable gases due to steam condensation must extend out into the reservoir. The data on non-condensable gases are not sufficiently accurate to help evaluate this possibility. (The 10 March samples were analyzed during the time when the gas partitioner recorder was found to have erratic electronic instability.)

The results are inconclusive regarding possible relation of radon concentration and flowrate. The 1 February flowrate of about *77,000* lb/hr is about 10% lower than the 2 February flowrate of about 815,000 lb/hr at the times (about 6 and 5 hours respectively) when the last samples were taken. Those samples had identical concentrations of 4300±170 pCi/l. Straight line interpolation between the last two samples taken on 1 February gives an expected concentration of about 4500 pCi/l at 5 hours after start of test flow. Assuming about the same standard deviation, this would be slightly (about 4%), though not significantly, higher than the value observed in the 5 hour sample on 2 February. The 10 March flowrate from 5 hours after start of test flow to the end of the drawdown is about 120,000 lb/hr; or about 141% of the 1 February flowrate and about 156% of the 2 February flowrate. The average concentration for the samples taken on 10 March at four or more hours after start of test flow was about 4040 pCi/l. This is about 6% less than the concentrations measured in the last samples taken on 1 and 2 February. The standard deviations of the individual measurements were about 4%. Furthermore, since the last samples on 1 and 2 February may not represent full decline to steady state concentrations, there is apparently no significant difference in radon-condensate concentrations for the different flow rates observed in this series of tests. It is possible that this apparent lack of dependence is simply the result of such short tests with total time of flow only a small fraction of the two weeks or more that would be required for radioactive equilibrium to be established. During such short tests it may be expected that the well would be producing stean whose radon content would have been at secular equilibrium under essentially non-flow conditions.

Most of the radon-$CO_2$ concentrations during the flow tests on 1 and 2 February are relatively constant with values between 70,000 and 80,000 pCi/l with standard deviations ranging from about 13 to 115% of the measured values. Two of the bleeding rate samples had somewhat lower concentrations, 58,000±6000 and 56,000±6000 pCi/l; while one was higher, 100,000±11,000 pCi/l. (The 10 March non-condensable gas data are not considered because of the known apparatus instability.) Within the limits of the generally large standard deviations it appears that the radon-$CO_2$ concentration is constant and does not vary significantly with flow rate or length of time from start of test flow. A comparison with the bleeding rate samples taken from well IV-C on 17 January can also be made. The 17 January samples had radon-$CO_2$ concentrations of 126,000±13,000 pCi/l to 169,000~18,000pCi/l. These values are generally about twice the measured values for samples taken on 1 and 2 February. However, the difference may not be significant because of the large standard deviations for the 1 and 2 February samples. An alternate explanation is that the non-condensable gas composition may in fact change over time due to changes in the geochemical process in the reservoir.

The second sequence of measurements during performance testing were made on samples taken from well IV-D, which reaches a total depth of *7024* ft in the Franciscan graywacke of the Geysers area. The well-head elevation is 2930 ft; the casing extends to a depth of 2501 ft and the hole is open below that level to the bottom. The bottom of this well is about 560 ft higher than well IV-C, and is about 1.5 miles distant.

Drawdown runs were made on three successive days, 27 through 29 March, 1974. The data are presented in Table 13. The radon-condensate concentrations and steam flow rates are shown in Figure 12.

The basic results of this series of measurements are qualitatively similar to those noted for the tests on well IV-C. The bleeding rate sample had a higher radon-condensate concentration and non-condensable gas volume to condensate volume ratio than any of the samples taken at higher flow rates. Samples were taken at high flow rates to at least the eighth hour of all three drawdown runs in an attempt to verify the apparent approach of radon-condensate concentrations to a steady state level as noted in the tests on well IV-C. Two of the sequences, on 27 and 28 March, **show** such a leveling in samples taken at four or more hours after start of test flow. The third, on 29 March, does not.

The single bleeding rate sample taken prior to start of the draw-down run on 28 March had a radon-condensate concentration of 18,400±700 pCi/l, about 6 times the average value observed in the samples at four

## Table 13

Summary of Data

Well IV-D Geysers Area 27 and 29 March 1974

Sampled during Pressure Drawdown Tests

| | 27 March 1974[1/] | | | [2/] | | | |
|---|---|---|---|---|---|---|---|
| Time of Sample | 12:23 | 14:25 | 16:25 | [illegible] | [illegible] | [illegible] 30 | [illegible] |
| Radon Concentration of Sample at Time of Collection, [illegible] | [illegible] | 80 | 68 | 82 | 75 | 76 | 91 |
| Volume of Condensate, ml | 57 | 184 | 180 | [illegible] | 108 | [illegible] | 93 |
| Volume of Non-Condensable Gases, cm$^3$, (0°C, 760mm Hg) | 26±16 | [illegible]±16 | 56 | 38 | 12±16 | 25±16 | 8±16 |
| Volume of $CO_2$ cm$^3$ (0°C [illegible] mm Hg) | 3.9 | 5 5 | 6 3 | 2.[illegible] | 1 1 | [illegible] 0 | 5 5 |
| Gas Analysis, Volume % | | | | | | | |
| $CO_2$ | 15.0 | 19.7 | 11.2 | 6.2 | 9.5 | 58.7 | 68.4 |
| $CH_4$ | [illegible] 9 | 8.9 | 4 6 | 2 [illegible] | 1.0 | 0 8 | 1 2 |
| $O_2$ | [illegible] 7 | 45 2 | [illegible].0 | [illegible].0 | [illegible].0 | 7 3 | 9 8 |
| $N_2$ | 16.5 | 7.6 | 6.8 | 20.9 | 29.4 | 10.7 | 16.2 |
| $H_2$ [3/] | 50.9 | 18.6 | 13.4 | 5.6 | 47.1 | 22.5 | 4.4 |
| Radon Concentration, pCi/liter[4/] | | | | | | | |
| Condensate[5/] | [illegible] 80 | 370 | 38[illegible] | [illegible]60 | [illegible] | [illegible] 90 | [illegible]70 |
| $CO_2$ | (15±9)x10$^4$ | (13±8)x10$^4$ | 11x10$^4$ | 18x10$^4$ | (42±55)x10$^4$ | (2.6±1.7)x10$^4$ | (5.5±11)x10$^4$ |

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[1/] Test flow started at 08:25

[2/] Test flow started at 07:30

[3/] Values assumed as balance to make 100%

[4/] Apparent concentration ratio of radioactivity to condensate or gas collected in sample

[5/] Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

Table 13 (continued)

Summary of Data

Well IV-D Geysers Area 28 March 1974

Sampled during Pressure Drawdown Test[1/]

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time of Sample | 07 [illegible] [2/] | 0 [illegible] | 0[illegible] C5 | 1 [illegible] | [illegible] 03 | [illegible] | 1 :45 |
| Radon Content of Sample at Time of Collection, pCi | 4130 | 823 | 581 | 353 | 332 | 343 | 388 |
| Volume of Condensate, ml | 225 | 130 | 120 | 106 | 111 | 110 | 116 |
| Volume of Non-Condensable Gases cm$^3$, (0°C, 760mm Hg) | 20 | 10 | 2 | $2 \pm 5$ | $18 \pm 16$ | $10 \pm 1$ | 6 |
| Volume of CO$_2$, cm$^3$, (0°C 760mm Hg) | 10 | 8 | 2 | 0 1 | 9 7 | 1 6 | 12 |
| Gas Analysis, Volume % | | | | | | | |
| CO$_2$ | 6.0 | [illegible] | 5 3 | 6.4 | 3 8 | 16.4 | 8 1 |
| [illegible] | 0.0 | 1.0 | 1.0 | 4.8 | 2 0 | 13.[illegible] | 8.5 |
| O$_2$ | 0 1 | 5 2 | 8 3 | 4.9 | 8.9 | 8 7 | 6.2 |
| N$_2$ | 1.0 | 1 1 | 18 2 | 2.0 | 1.0 | 0 6 | 3 6 |
| H$_2$ [3/] | [illegible] | 6.0 | 0 7 | 6.9 | 4.0 | [illegible] | .6 |
| Radon Concentration, pCi/liter[4/] | | | | | | | |
| Condensate[5/] | 18400 | 6330 | 4840 | 3330 | 2990 | 3120 | 3340 |
| CO$_2$ | $2.4\times 10^4$ | $4.6\times 10^4$ | $(4.9 \pm 3.5)\times 10^4$ | $(270 \pm 190)\times 10^4$ | $(3.4 \pm 3.1)\times 10^4$ | $(21 \pm 36)\times 10^4$ | $3.3\times 10^4$ |

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1/ Test flow started at 07.45

2/ Sample taken at bleeding rate, approximately 500 lb/hr

3/ Values assumed as balance to make 100%

4/ Apparent concentration: [illegible] collected in sample

5/ Divide by 1,670 to obtain [illegible] in saturated steam at 1 atmosphere pressure

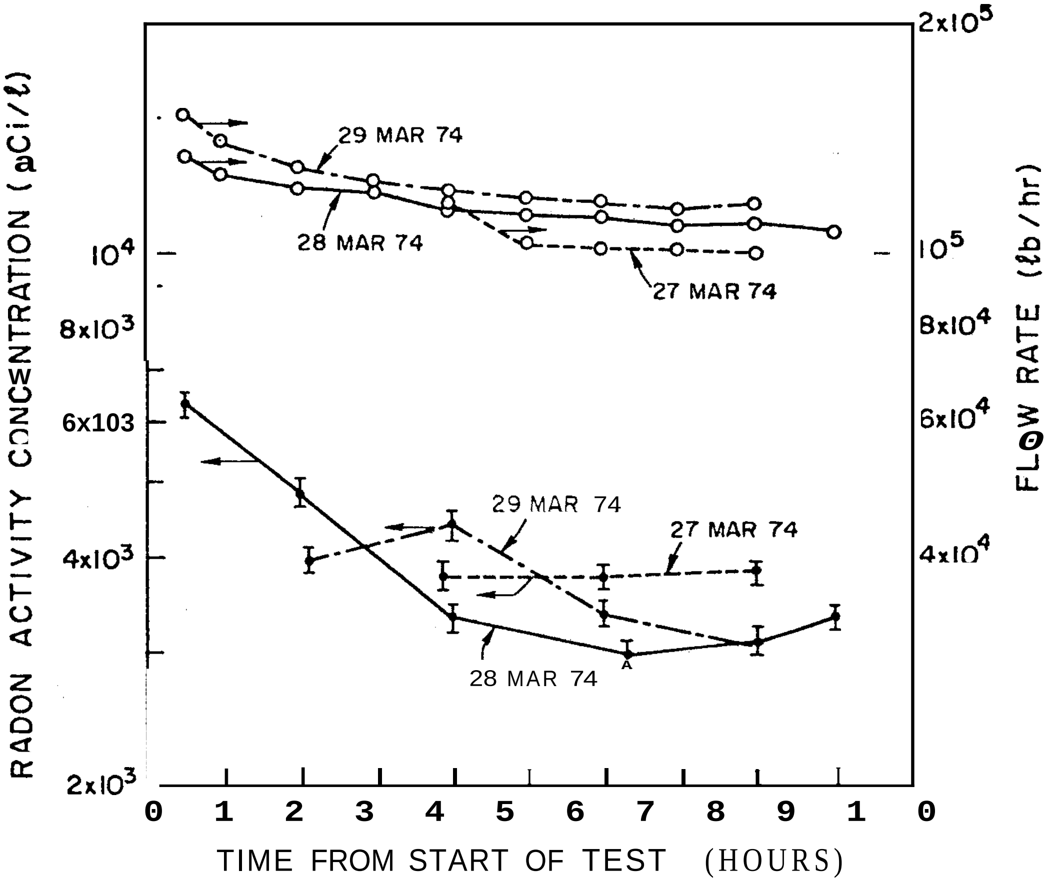

Figure 12. Radon activity concentration* and flow rate during pressure drawdown test, Geysers Area, Well **IV-D.**

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* Apparent concentration: ratio of radon activity to condensate or gas collected in sample; divide by 1,670 to obtain approximate concentration in saturated steam at **1** atmosphere pressure.

or more hours after start of test flow on that day. The $CO_2$-condensate volume ratio in the bleeding rate sample is about 14 times the average of the ratios observed in the samples at four or more hours. This tends to confirm the general enrichment of non-condensables at bleeding rates, though the individual non-condensable gas volumes in the last four samples have standard deviations of about 25 to 700%.

Samples taken after the start of high flow rates for the drawdown generally show patterns of declining radon-condensate concentrations similar to those observed during the tests on well IV-C. The 27 and 28 March data show nearly constant values for radon-condensate concentrations in samples taken at four or more hours after start of test flow. The three such samples from 27 March have an average concentration of 3790 pCi/l; the individual measurements differ from this average by 10 to 30 pCi/l (about 0.2 to 0.8%) and have individual standard deviations of 150 pCi/l (about 4%). The four such samples from 28 March hove an average concentration of 3200 pCi/l; the individual measurements differ from this average by 80 to 210 pCi/l (about 3 to 7%) and have individual standard deviations of 120 to 140 pCi/l (about 4%). The three samples taken at four or more hours on 29 March show a monotonic decline from 4400±180 pCi/l to 3070±130 pCi/l. These values have an average of 3620 pCi/l; the individual measurements differ from this average by 230 to 780 pCi/l (about 6 to 21%) and have standard deviations of 130 to 180 pCi/l (about 4%). There were no obvious difficulties during sampling or analysis that night explain the anomalous pattern in the 29 March data. The variation in radon-condensate concentrations in this sequence might be related to inhomogenieties in the emanating power of the formation. A "puff" of steam that had Seen in radioactive equilibrium with a high emanating-power portion of the formation might have reached the wellbore during the third day of testing.

The data from the 27 and 28 March drawdowns give a possible indication of inverse relation between radon-condensate concentrations and flow rats. The average concentrations in samples taken at four or more hours were, respectively, 3790 pCi/l and 3200 pCi/l. All but one of the individual measurements were within one standard deviation of their respective means. Thus, the average for the 28 March values is about 13% lower than the average for the 27 March values. The average flow rate at four or more hours on 28 March was about 110,000 lb/hr, about 6% higher than the corresponding value of about 104,000 lb/hr on 27 March. Thus, there is an apparent 13% decline in radon-condensate concentration corresponding to a 6% increase in flow rate. This result differs from the tests on well IV-C where a 41 to 56% increase in flow rate corresponded to a decline in radon-condensate concentration of no more than 4%. As noted in the discussion of well IV-C data, it is not expected that a large variation in radon concentration would be observed during tests that are short compared to the two or more weeks needed for radioactive equilibrium. This expectation is predicated on the assumptions of uniform reservoir conditions including emanating power. Taking into consideration the variation in the 29 March data, it may be that well IV-D is located in a less uniform part of the reservoir. The observed variation in radon concentrations at times of four or more hours may be more dependent on these possible inhomogeneities than on flow rates or times.

A corroborating piece of evidence for the possible reservoir inhomogeneities is in the radon-$CO_2$ concentrations observed in the samples taken during the drawdown tests of well IV-D. The values of these concentrations for well IV-D have a larger range, from 26,000 ± 17,000 pCi/l to 2,700,000 ± 1,900,000 pCi/l, than those for well IV-C. In spite of the large standard deviations of these concentrations, they are more irregular than the concentrations observed in the 1 and 2 February samples for well IV-C (see Table 12).

Finally, it can be noted that the $CO_2$ and $CH_4$ percentages are in a more nearly constant ratio in the samples taken from well IV-C than in samples from well IV-D. For well IV-C the $CO_2$ volumetric percentage is 3.8 to 5.6 times the $CH_4$ volumetric percentage in the 1 and 2 February samples. For well IV-D the $CO_2$ volumetric percentage is 1.2 to 73 times the $CH_4$ volumetric percentage. Thus, the non-condensable gas composition in fluids from well IV-D appears to vary much more than from well IV-C.

Measurement during Production--Samples were taken from 9 production wells which belong to three groups divided according to physical proximity and depths. Wells in groups I and II are in the deeper steam formation identified at The Geysers, and those in Group III are in the shallower formation. The wells in Group I range in depth from about 2900 to 4700 ft, those in Group II range from about 1750 to 2500 ft, and those in Group III range from about 550 to 800 ft.

Five samples were taken from well I-A during a period of about 24 hours to examine the constancy of radon concentration. During this period the well flowed at a nearly constant rate. The data are presented in Table 14. The radon-condensate concentrations and the steam flow rates are shown in Figure 13.

The average of the flow rates at the times of sampling was 66,100 lb/hr and the individual rates were all within 1.5% of the average. The average radon-condensate concentration was 17,300 pCi/l with individual values ranging from 4.9% below the average to 4% above the average. The standard deviation of individual measurements was about 3.8%. Thus the radon-condensate concentration is inferred to be constant during the sampling period.

Consideration of the other non-condensable gas data indicates that $CO_2$ and $CH_4$ varied considerably during the sampling period. The radon-$CO_2$ concentration ranged from about 8000 to 600,000 pCi/l, a much larger variation than can be attributed to experimental error. The ratio of volumetric percentages of $CO_2$ to $CH_4$ ranged from about 0.1 to 5.7.

Six samples were taken from well I-B during a period of about 24 hours. During this period the well was flowed at several different rates. The data are ?resented in Table 15. The radon-condensate concentrations and the steam flow rates are shown in Figure 14.

The first two samples were taken within a few minutes of each other to provide a check on sanpling consistency. The radon-condensate concentrations agree well within the estimated limits of error in measurement.

Table 14

Summary of Results

W ell I A$^{1/}$ Geysers Area 22 and [illegible] April 1974

Sampled during Production

| | 22 April 1974 | | | | |
|---|---|---|---|---|---|
| Time of Sample | 16:08 | 08 [illegible] | 10 07 | [illegible] | [illegible] |
| Radon Content of Sample at Time of Collection, pCi | 1690 | 1870 | 1900 | 1750 | 1860 |
| Volume of Condensate ml | [illegible]3 | [illegible]8 | 107 | 9 | 19 |
| Volume of Non-Condensable Gases, cm$^3$, (0°C, 760mm Hg) | 266 | 185 | 163 | 162 | 578 |
| Volume of $CO_2$, cm$^3$ (0°C 760mm Hg) | 10 | [illegible] | [illegible] | [illegible] | [illegible] |
| **Gas Analysis, Volume %** | | | | | |
| $CO_2$ | [illegible] 5 | [illegible] 5 | [illegible] 6 | 1 8 | [illegible] |
| $O_2$ | 0.4 | 0.3 | 1.0 | 0 3 | 0 2 |
| $N_2$ | [illegible] 1 | 4.4 | 8 [illegible] | 20 5 | 7 0 |
| $CH_4$ | [illegible] 5 | [illegible].0 | [illegible] 2 | [illegible] 5 | 9 2 |
| $H_2$ | [illegible].0 | [illegible].0 | not measured | | |
| Total | 101.5 | 101.2 | -- | -- | -- |
| **Radon Concentration, pCi/liter**$^{2/}$ | | | | | |
| Condensate$^{3/}$ | 1500 | [illegible]400 | [illegible]700 | [illegible]000 | [illegible] |
| $CO_2$ | [illegible]000 | 4000 | [illegible]000 | 60000 | [illegible]00 |
| **Well Parameters** | | | | | |
| Flowrate, lb/hr | 6100 | 65[illegible]0 | 6[illegible]00 | 6[illegible]00 | 6500 |
| Wellhead Pressure, psig | [illegible] | [illegible] | 14[illegible] | 134 | [illegible] |

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1/ Well depth 2888 ft, wellhead elevation 1854 ft (MSL), wellhead temperature 362°F.

2/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

3/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

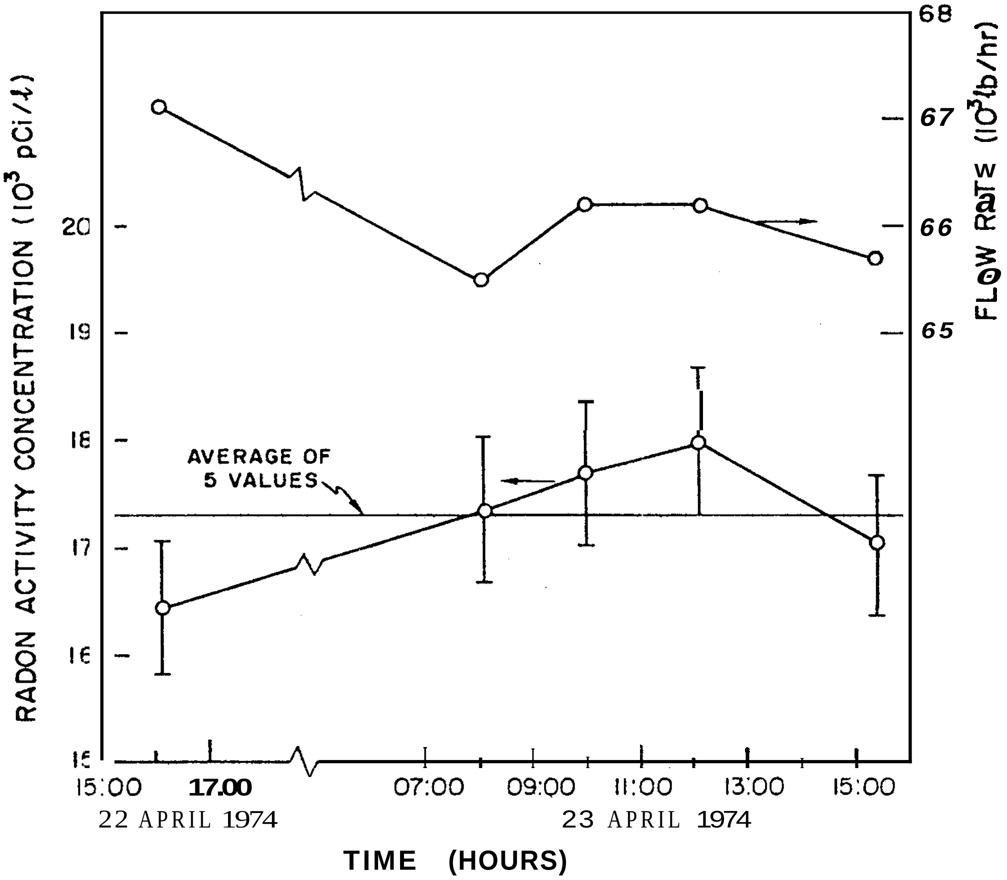

Figure 13. Radon activity concentration* and flow rate for production well I-A, Geysers Area.

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* Apparent concentration: ratio of radon activity to condensate or gas collected in sample; divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure.

## Table 15

### Summary of Results

### Well I-B[1/] Geysers Area 22 and 23 April 1974

### Sampled During Production and Cleaning Operation

| | 22 April 1974 | | 23 April 1974 | | | |
|---|---|---|---|---|---|---|
| Time of Sample | 16:20 | 16:24 | 07:54 | 11:56[2/] | 13:52 | 15:15 |
| Radon Content of Sample at Time of Collection, pCi | 1510 | 1480 | 1520 | 491 | 1000 | 1140 |
| Volume of Condensate, ml | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Volume of Non-Condensable Gas, cm$^3$, (0°C, 760mm Hg) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 187 |
| Volume of CO$_2$, cm$^3$, (0°C, 760mm Hg) | | | | | | |
| Gas Analysis, Volume % | | | | | | |
| CO$_2$ | [illegible] | [illegible] | 1.0 | [illegible] | 18.5 | 59.7 |
| O$_2$ | 0.4 | 0.4 | 1.8 | 0.3 | 0.3 | 0.4 |
| N$_2$ | 5.0 | 4.6 | 88.5 | 3.8 | 7.8 | 5.6 |
| CH$_4$ | 15.0 | 10.6 | 4.7 | 9.7 | 10.0 | 11.2 |
| H$_2$ | | | not measured | | | |
| Radon Concentration, pCi/liter[3/] | | | | | | |
| Condensate[4/] | [illegible] | [illegible] | 8000 | [illegible] | 9430 | 10200 |
| Gas | 1000 | [illegible] | 10000 | 1000 | [illegible] | 10000 |
| Well Parameters | | | | | | |
| Flowrate, lb/hr | [illegible] | [illegible] | [illegible] | >14 000 | [illegible] | 110800 |
| Wellhead Pressure, psig | [illegible] | [illegible] | [illegible] | ~[illegible] | 13 | 133 |

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1/ Well depth 3955 ft, wellhead elevation 1920 ft (MSL), wellhead temperature 428°F.

2/ Well open to atmosphere for cleanout of grit.

3/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

4/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

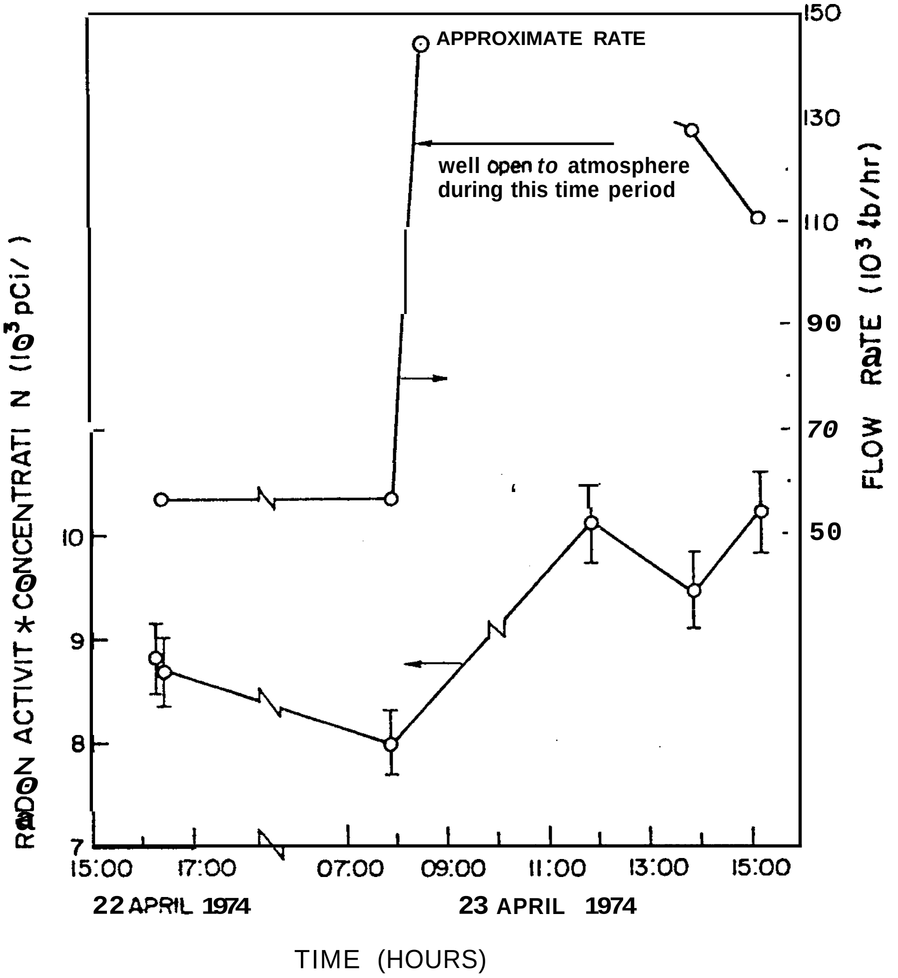

Figure 14. Radon activity concentration* and flow rate for production well I-B, Geysers Area.

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* Apparent concentration: ratio of radon activity to condensate or gas collected in sample; divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure.

The two measurements have an average of 8750 pCi/l and each is within 1% of the average. The standard deviation of the individual measurements is about 3.8%. The third sample, taken about 16 hours later when the well was still flowing at the same rate, is about 8.6% lower than the average of the first two. It also has standard deviation of about 3.8%. However, this difference of 8.6% is about the same as the difference between the highest and lowest radon-condensate concentrations *(8.37)* observed in the series of samples taken from well I-A. Thus, the radon-condensate concentration is inferred to be constant for well I-B during the period when it flowed at a constant rate of about 56,800 lb/hr.

Shortly after the third sample was taken, the well was vented to the atmosphere--a cleaning process to eliminate grit and stones from the wellbore prior to connection to steam lines supplying the generating station. The vented well flowed for a period of about 4 hours at a rate of about 140,000 lb/hr. One sample was taken about 3.5 hours after initiation of the high flow rate. This sample had a radon-condensate concentration of 10,100 pCi/l, about 19% higher than the average of the first three samples (8500 pCi/l) taken at the low flow rate. The standard deviation of this concentration was about 4%, and thus there appeared to be a measurable increase in radon-condensate concentration at the higher flow rate.

The last two samples from well I-B were taken after the well was connected to the steam delivery line. These two samples had radon-condensate concentrations about 6.6% lower and 1% higher than the sample taken while the well was venting to the atmosphere. These two samples had standard deviations of measuremenr of about 4%. Thus the last three samples probably had a nearly constant radon-condensate concentration. They have an average of 9910 pCi/l which is about 17% higher than the average of the first three samples. A possible explanation is that the drastic reduction in wellhead pressure caused a sufficient drop in formation pressure to induce a higher effective emanation power by the mechanism of releasing previously immobilized gases from tiny pores and microfractures in the rocks. An analogous effect is known to result in increased radon flux from soil or increased radon concentration in shallow water wells as atmospheric pressure declines (Clements and Wilkening, 1974).

The non-condensable gas data for the samples from well I-B showed an irregular variation similar to that observed in samples from well I-A. The radon-$CO_2$ concentration ranged from 5800 to 140,000 pCi/l, a much larger variation than can be attributed to experimental error alone. The variations show no apparent relation to the changes in flow rate. The ratio of volumetric percentages of $CO_2$ to $CH_4$ ranges from 0.2 to 6 which is almost the same range as observed in the samples from well I-A. Thus, the samples from both wells I-A and I-B indicate that there are significant short-time variations in the absolute amounts and proportions of $CO_2$ and $CH_4$, The first two samples from well I-B indicate that these variations can occur in periods of only a few minutes. The variations may be attributable to inhomogeneities in the sources of the $CO_2$ and $CH_4$ or in the flow processes in the reservoir. It is not neceassarily surprising that radon-condensate concentrations are observed to be more uniform because of the different sources of the gases.

Individual samples were taken from seven other producing wells at The Geysers. The data for these samples are presented in Table 16. The four wells in Group I (including average values from wells I-A and I-B) had an average radon-condensate concentration of 18,400 pCi/l with a range of 9200 to 25,700 pCi/l. The three wells in Group II had an average radon-condensace concentration of 27,300 pCi/l, with a range of 26,300 to 31,400 pCi/l. The two wells in Group III had an average radon-condensate concentration of 16,900 pCi/l, with a range of 16,300 to 17,500 pCi/l. There is no apparent correlation of radon-condensate concentration and depth within Groups I and II. The radon-condensate concentrations in the two samples from Group III are not significantly different. Considering only the average values for each group, Group II (those of intermediate depth) has a higher value than either Group I (the deepest wells) or Group III (the shallow wells). However, only one of the samples from Group II has a value higher than the maximum

Table 16

Summary of Results

Production Wells Geysers Area 23 April 1974

Sampled During Production

| Well Identification | I-C | I-D | II-A | II-B | II-C | III-A | III-B |
|---|---|---|---|---|---|---|---|
| Radon Content of Sample at Time of Collection, pCi | 2590 | 2640 | 2760 | 3520 | 2590 | 1830 | 1810 |
| Volume of Condensate, ml | 126 | 99 | 105 | 112 | 107 | 112 | 103 |
| Volume of Non-Condensable Gas cm$^3$, (0$^\circ$C, 760mm Hg) | 37 | 23 | 53 | 61 | [illegible] | [illegible] | 7 |
| Volume of CO$_2$, cm$^3$, (0$^\circ$C, 760 mm Hg) | 90 | 80 | 30 | [illegible]10 | 20 | 5 | [illegible] |
| **Gas Analysis, Volume %** | | | | | | | |
| $CO_2$ | 61.0 | 5 5 | [illegible] | [illegible] 5 | [illegible].0 | [illegible].0 | [illegible] 5 |
| $O_2$ | 0.0 | 0 2 | 0 0 | 0 1 | 0 1 | 0.4 | 0 3 |
| $N_2$ | 2 1 | 3 2 | 3 5 | 3.0 | 1 9 | 7 5 | [illegible] 5 |
| $CH_4$ | 12.5 | 13.0 | 19.5 | 11.9 | 9.5 | 14.0 | 7.6 |
| $H_2$ | | | not measured | | | [illegible].0 | [illegible] 5 |
| Total | -- | -- | -- | -- | -- | 100.0 | 102.4 |
| **Radon Concentration, pCi/liter**1/ | | | | | | | |
| Condensate2/ | [illegible] | [illegible]700 | [illegible]300 | 314 0 | [illegible] | [illegible]300 | 1500 |
| $CO_2$ | [illegible]00 | 1000 | [illegible] | 600 | 2000 | 80000 | 4 [illegible] |
| **Well Parameters** | | | | | | | |
| Flowrate, lb/hr | 8900 | 2 [illegible]0 | 6900 | 9000 | 9600 | 8200 | 8200 |
| Wellhead Pressure, psig | 132 | 130 | 134 | 132 | 135 | 103 | 105 |
| Wellhead Temperature, $^\circ$F | 392 | 351 | 368 | 379 | 371 | 356 | 360 |
| Wellhead Elevation, ft (MSL) | 1969 | 2014 | 1888 | 1860 | 2940 | 1648 | 1699 |
| Well Depth, ft | 3929 | 4689 | 2515 | 1790 | [illegible] | 58 | 8 [illegible] |

1/ Apparent concentration: ratio of radon activity to condensate or gas collected in sample

2/ Divide by 1,670 to obtain approximate concentration in saturated steam at 1 atmosphere pressure

observed in Group I. All of the samples taken from the production wells in Groups I, II, and III had radon-condensate concentrations (about 9000 to 31,000 pCi/l) higher than those taken at approximately steady state performance test conditions from wells **IV-C** and **IV-D** (about 3000 to 5000 pCi/l). Thus there are significant differences in the amounts of radon observed in samples taken from wells in the same field and in different fields.

The non-condensable gas data for the individual samples (Table 16) show variations between wells similar to those for samples taken from single wells at different times (Tables 14 and 15). Radon-$CO_2$ concentrations in the individual samples (Table 16) range from 5800 to 380,000 pCi/l. The ratios of volumetric percentages of $CO_2$ to $CH_4$ range from 0.9 to 7.2.

~~Related~~ Study--A study was performed by Pacific Gas and Electric Co. in 1973 and 1974 which included measurements of radon in the steam supply to generating plants at The Geysers, in the ejector off-gases from the power plants, and in ambient air in and around the power plants (Mark Mathisen, P.G. & E., personal communication). The report of that study, dated May 13, 1974, includes some data that can be compared to the results described in this section.

The P.G. & E. report gives four measurements of radon in the steam supply ranging from 5.0 to 8.3 pCi/l of steam at 700 mm Hg pressure. The measurements of radon in the steam from production wells at The Geysers made for this study range from approximately 9000 to 31,000 pCi/l of steam condensate. If these values are converted, they indicate a range of about 4.9 to 17 pCi/l of saturated steam at 700 mm Hg pressure. Thus, there is substantial agreement between the measurements of radon content in relation to steam for measurements at the wellhead and at the operating plants. It is not known whether the wells sampled at the wellhead were among the wells connected to the delivery lines from which the power plant samples were taken.

The P.G. & E. report also gives four measurements of radon in ejector off-gases ranging from 2780 to 5300 pCi/l, and four measurements of radon in non-condensable gases from steam supply ranging from 5800 to 6300 pCi/l. Because of differences in sampling techniques, and the lack of specification of pressure and temperature conditions for the gases in the P.G. & E. report, the data are not directly comparable to the values reported in this study. However, there is some qualitative agreement in that the lowest radon-$CO_2$ concentrations observed in well-head samples taken in this study were 5800 pCi/l.

### Sampling of Wells in Liquid Dominated Systems

Low Flow Rate Sampling--Samples were taken from two wells in the East Mesa KGRA. The data were presented in Tables 10 and 11.

Well 6-2 reached a total depth of 6005 ft. It was cased from the surface to a depth of *5445* ft and slotted from that depth to 5951 ft. The bottom hole temperature is about 370°F. The fluid produced from the well had a total dissolved solids content of about 2300 ppm (John Featherstone, Bureau of Reclamation, personal communication). A total of seven samples were taken from well 6-2.

Three samples were taken on 30 November 1973 (Table 10) by the flow through technique. These samples had an average radon-condensate concentration of about 12 pCi/l. They are not considered reliable because of the probability of gas loss during sampling.

Four samples were taken on *14* February *1974* by the evacuated cylinder technique. The well had been flowing at a rate of about 25 gal/min for 16 hours prior to sampling. This was assumed to be adequate to completely flush the wellbore of standing fluid and provide a sample representative of the formation fluid. The low flow rate prevented any flashing from occurring in the wellbore *so* the samples should be representative of the liquid. The samples had an average radon-condensate concentration of 34.2 pCi/l, with a range from 31.7 to 36.2 pCi/l and individual errors in measurement ranging from 1.5 to 1.6 pCi/l. Two of the four samples were analyzed for dissolved radium. The dissolved radium content of these samples was computed to be 0.12 and 0.16 pCi/l or less than 0.5%

of the average total radon content of the samples.

Well 6-1 was located 1475 ft away from well 6-2 and reached a total depth of 8030 ft. At the time of sampling it had been packed at about 7203 ft and perforated a total of about 185 ft at intervals between 6187 and 7128 ft. The bottom hole temperature was about 400°F. Well 6-1 had been flowed at varying low rates for several hours prior to sampling. The sample was considered to be representative of the formation fluid because of the high dissolved solid content, about 25,000 ppm (John Featherstone, Bureau of Reclamation, personal communication). (The well had been filled with low salinity water the previous day to "prime" the test system.) Analysis of this sample (Table 11) showed a total radon-condensate concentration of 68.9 pCi/l, about twice the level observed in samples from well 6-2. However, the dissolved radium in the single sample from well 6-1 had a concentration of about 29.4 pCi/l, or more than 200 times the average (0.14 pCi/l) of the samples from well 6-2. These data indicate that there are significant differences in the liquids in the reservoir over relatively small distances.

Steam Separator Sampling--A series of 14 samples were taken from well Magmamax #1 in the Salton Sea KGRA. The well reached a total depth of 2250 ft and was perforated from about 1800 ft to the bottom of the hole. The samples were taken while the well was being produced for the purpose of testing the operation of a steam separator. The well flowed intermittently at different rates during the sampling period. The data are presented in Table 17. The radon-condensate concentrations (normalized to total mass flow) and flow rates are shown in Figure 15.

The wellhead samples wire not considered reliable because of poor sampling conditions. The sampled fluid had to flow through about 5 ft of 2 in pipe elbowed into the wellhead. The well flow rates were such that flashing occurred in the well bore and two-phase flow existed at the wellhead. Thus it was not likely that representative samples were obtained.

The separator samples were taken at the steam outlet of the

## Table 17

### Summary of Results

Magmamax #1 Salton Sea KGRA 8 and 9 April 1974

Sampled during steam separator tests

| | 8 April 1974 | | | | 8 April 1974 | | | | 9 April 1974 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total-Flow Wellhead Samples | | | | Separated Steam Samples | | | | Separated Steam Samples | | | | | |
| Time of Sample | 11:30 | 15:05 | 15:17 | 15:35 | 11:47 | 15:10 | 15:21 | 15:40 | 9:22 | 9:[illegible]8 | 10:15 | 10:37 | 10:[illegible] | 10:55 |
| Radon Content of Sample at Time of Collection, pCi | 698 | 17.1 | 367 | 250 | 523 | 319 | 479 | 257 | 665 | 567 | 902 | 1050 | 980 | 450 |
| Radon in Equilibrium with Dissolved Radium, pCi | 251 | not measured | not measured | 250 | | | | | | | | | | |
| Volume of Condensate, ml | [illegible] | [illegible] | 87 | [illegible] | [illegible]7 | [illegible] | [illegible] | 11 | [illegible] | 1[illegible]2 | [illegible]3 | [illegible]7 | [illegible]3 | [illegible] |
| Volume of Non-Condensible Gases cm³, (0°C, 760 mm) | 36 | - | [illegible] | [illegible] | 983 | [illegible] | [illegible]6 | 20 | [illegible]5 | [illegible] | [illegible]30 | [illegible]50 | 120 | [illegible]40 |
| Gas Analysis, Volume % | | | | | | | | | | | | | | |
| $CO_2$ | 98.0 | -- | 0.0 | 90.0 | 105.0 | 90.0 | 76.0 | 75.0 | 102.0 | 103.0 | 106.0 | 103.0 | 104.0 | 87.0 |
| $O_2$ | 0.0 | -- | 9.0 | 2.5 | 0.2 | 0.3 | 0.1 | 0.[illegible] | 0.0 | 0.4 | 0.0 | 1.0 | 0.4 | 0.0 |
| $N_2$ | 5.0 | -- | 88.0 | 10.0 | 1.5 | 8.0 | 1.0 | 2.0 | 1.6 | 1.6 | 0.4 | 3.5 | 0.6 | 11.0 |
| $CH_4$ | 2.0 | -- | 0.0 | 1.0 | 0.2 | 0.4 | 1.0 | 1.0 | 1.8 | 0.8 | 0.9 | 1.5 | 0.8 | 0.8 |
| $H_2$ | 5.0 | -- | 14.5 | 5.5 | 5.1 | 11.9 | 34.9 | [illegible].0 | 5.1 | 2.2 | 4.1 | 3.0 | 5.8 | 9.8 |
| Total | 110.0 | -- | 111.5 | 109.0 | 112.0 | 110.6 | 113.0 | 1[illegible].2 | 110.5 | 108.0 | 111.4 | 112.0 | 111.6 | 108.6 |
| Radon Concentration, pCi/liter[1] | | | | | | | | | | | | | | |
| Condensate in Sample | 659 | 439 | 3870 | 538 | 5390 | 2030 | 3320 | 2320 | [illegible]720 | 2960 | 6130 | 5330 | 4830 | 2830 |
| Total Mass Flow | 659 | 439 | 3870 | 538 | 799 | [illegible]07 | 501 | [illegible]22 | 302 | 329 | 487 | 712 | 645 | 375 |
| $CO_2$ | 2130 | -- | -- | -- | 532 | 118 | 1100 | 1250 | 930 | 545 | 521 | 778 | 742 | 417 |
| Separator Flow Conditions | | | | | | | | | | | | | | |
| Separator Steam Flow, $10^3$ lb/m | -- | -- | -- | -- | 10.3 | 15.3 | 15.3 | 12.0 | 1[illegible].5 | 1[illegible].5 | 7.7 | 7.4 | 7.4 | 7.4 |
| Separator Brine Flow, $10^3$ lb/m | -- | -- | -- | -- | 59.2 | 86.0 | 86.0 | 54.0 | 1[illegible]0.0 | [illegible] | 92.0 | 48.0 | 48.0 | 48.0 |
| Total Mass Flow, $10^3$ lb/m | 69.5 | 101.3 | 101.3 | [illegible]6.0 | 69.5 | 101.3 | 101.3 | 66.0 | 1[illegible].5 | 1[illegible].5 | 99.7 | 55.4 | 55.4 | 55.4 |

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[1] Apparent concentration: Ratio of radon activity to condensate or gas collected in sample

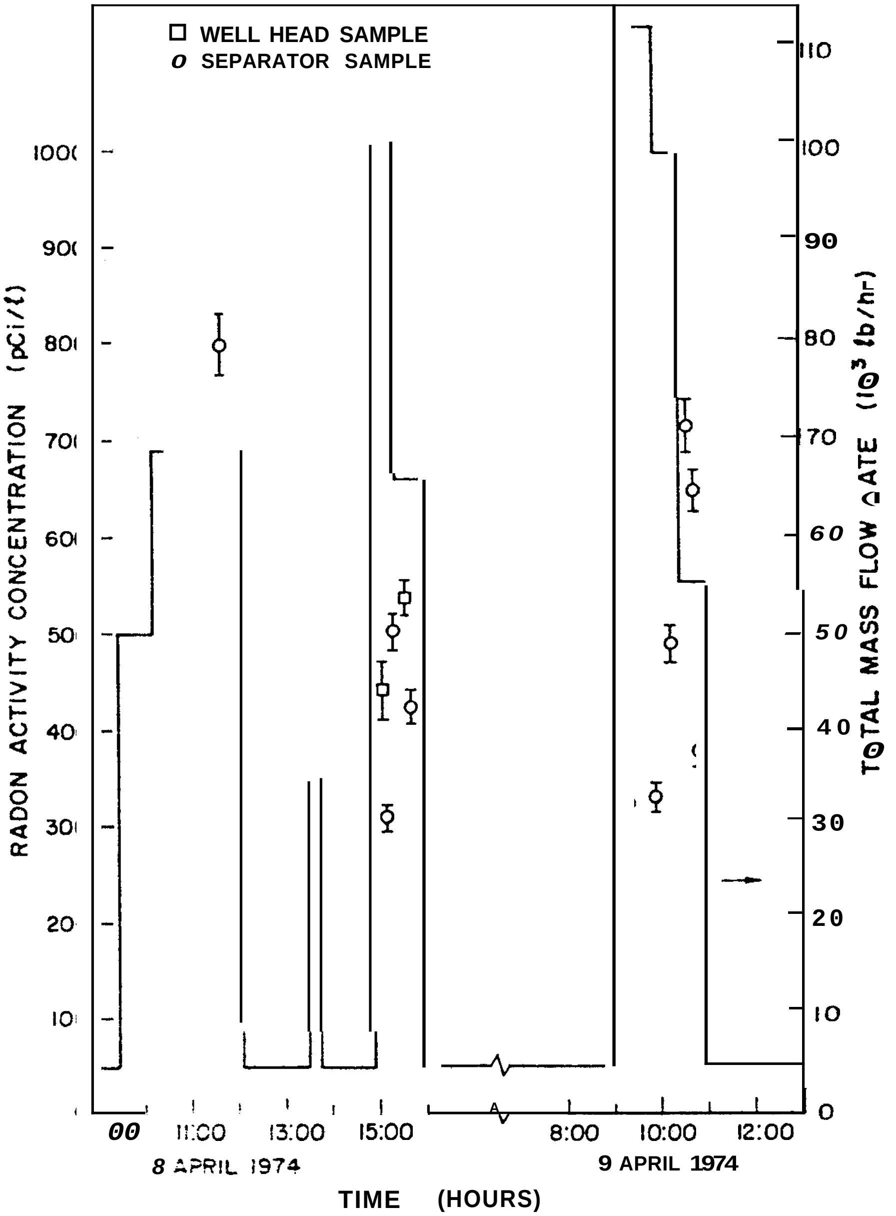

Figure 15. Radon activity concentration* in total flow and production rate for Magmamax # 1.

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* Apparent concentration: ratio of radon activity to Condensate or gas collected in sample,

separator. It was assumed that essentially all radon would be associated with the steam released by flashing in the separator because more than 98 percent of the $CO_2$ is associated with the steam from the separator (Gil Lombard, San Diego Gas and Electric Co., personal communication).

Four sets of paired wellhead and separator samples were taken on 8 April 1974. The first pair of samples taken at a total mass flow rate of $69.5 \times 10^3$ lb/hr had radon-condensate concentrations (normalized to total mass flowrate) of 659 pCi/l at the wellhead and 799 pCi/l at the separator. These were the highest values observed in all samples of their respective types. The second pair, taken at a total mass flowrate of $101.3 \times 10^3$ lb/hr had radon-condensate concentrations of 439 pCi/l at the wellhead and 307 pCi/l at the separator. These are respectively 33 and 62 percent lower than the first pair while the flow rate is 46 percent higher. In the third pair, also taken at a total mass flow rate of $10.13 \times 10^3$ lb/hr, the wellhead sample was considered anomalously high, and the separator sample is 63 percent higher than its counterpart in the second pair. The fourth pair of samples were taken at a total mass flow rate of $66.0 \times 10^3$ lb/hr, about 5 percent less than the flowrate for the first pair. However the wellhead sample in the fourth pair had a radon-condensate concentration of 538 pCi/l, about 18 percent lower then its first pair counterpart; and the separator sample had a concentration of 427 pCi/l, about 47 percent lower than its first pair counterpart. Thus, there is poor agreement between the wellhead and separator samples and there is poor agreement between the same type of samples taken at similar or identical flow rates. This may be attributable to the intermittent flow conditions which probably did not permit steady state conditions to be reached.

Six separator samples were taken on 9 April 1974 at three different flow rates. The first two samples were taken at the same flow rate, $112.5 \times 10^3$ lb/hr. They had radon-condensate concentrations of 302 and 329 pCi/l, showing good agreement. The third sample, taken at a total mass flow rate of $99.7 \times 10^3$ lb/hr (11% less than for the previous two samples) had a radon-condensate concentration of 487 pCi/l (54% higher than the average of the previous two samples). The last three samples, all taken at a total mass flow rate of 55.4 x $10^3$ lb/hr (51% lower than the flow rate for the first two samples) had radon-condensate concentrations ranging from 376 to 712 pCi/l (19 to 126% higher than the average of the first two samples). Thus, the pattern is irregular and there is poor agreement for the last three samples taken at the same flow rate.

The average of the radon content of all samples of fluid (excluding the one anomalously high wellhead sample) from well Magmamax #1 was about 500 pCi/l. The total dissolved solids content of the total mass flow was about 240,000 ppm (Gil Lombard, San Diego Gas and Electric Co., personal communication). Thus, the average radon-condensate concentration of samples from Magmamax #1 is about *14.6* times that of well Mesa 6-2 and 7.3 times that of well Mesa 6-1. The total dissolved solids content of total flow from Magmamax #1 is about 100 times that of well Mesa 6-2 and 9.6 times that of well Mesa 6-1.

## Environmental Sampling

A series of environmental radon measurements were made in a mountain valley of The Geysers area of Northern California. Radon concentrations were measured in samples taken from ambient air, air near steam wells undergoing test, and visible steam plumes from the wells. Four sets of samples were taken to provide an estimate of the natural flux of radon in soil gas. The results are presented in Table 18.

~~Air~~ Samples--Samples were taken at the lower end of the valley (near a hot spring) and at the ridge forming the upper boundary of the valley on two separate occasions about 2 months apart. On 10 March 1974, the radon concentration in the air sample taken at the lower end of the valley was 0.12 pCi/l, and in two samples taken at the ridge the concentrations were both less than 0.05 pCi/l. On 18 May 1974 the sample taken at the lower end of the valley had a radon concentration of less than 0.07 pCi/l. On 19 May 1974 the sample taken at the ridge had a concentration of 0.13 pCi/l. **All** of these values are less than the average

## Table 18
## Environmental Radon Measurements in Mountain Valley Environs of a Geothermal Well Field, Geysers Area

### Ambient Air Concentrations

| Date | Location | Radon Concentration 1/ (pCi/liter) |
|---|---|---|
| 17 Jan 1974 | ∿75' from bleeding well, still air | <0.05 |
| 17 Jan 1974 | ∿100' from bleeding well, still air | <0.05 |
| 2 Feb 1974 | ∿75' upwind from well under test @ ∿75000 lb/hr | <0.05 |
| 2 Feb 1974 | ∿75' downwind from well under test @ ∿75000 lb/hr | 0.16±0.02 |
| 10 Mar 1974 | ∿100' upwind from well under test @ ∿120000 lb/hr | <0.05 |
| 10 Mar 1974 | ∿300' downwind from well under test @ ∿120000 lb/hr (in steam cloud intercepting slope above well) | <0.05 |
| 10 Mar 1974 | at lower end of mountain valley near hot springs (Location 1) | 0.12±0.01 |
| 10 Mar 1974 | at ridge forming upper boundary of mountain valley, 2 samples (Location 3) | <0.05<br><0.03 |
| 29 Mar 1974 | ∿200' upwind of well under test @ ∿115000 lb/hr | <0.1 |
|  | ∿100' downwind of well under test @ ∿115000 lb/hr (in steam plume intercepting slope above well) | 0.25±0.03 |
| 18 May 1974 | at lower end of mountain valley near hot springs (Location 1) | <0.07 |
| 18 May 1974 | approximate midpoint of valley (Location 2) | 0.11±0.01 |
| 19 May 1974 | at ridge forming upper boundary of mountain valley (Location 3) | 0.13±0.01 |

### Soil Gas Flux Values

| | | Radon Flux ($10^{-5}$ pCi/$cm^2$-sec) |
|---|---|---|
| 28 Mar 1974 | Location 2 | 5.7±0.3 |
| 18 May 1974 | Location 1 | 5.5±0.3 |
| 18 May 1974 | Location 2 | 3.3±0.3 |
| 19 May 1974 | Location 3 | 1.3±0.1 |
| | World Average (Wilkening, et al., 1972) | 4.25 |

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1/ Actual radon concentration in air at 1 atmosphere pressure.

for air over land areas by factors of two or more.

Samples of Air Near Wells--Several sets of paired samples were taken within a few hundred feet up and downwind (as judged by the direction of steam plumes) of wells flowing at bleeding rates or performance test rates. On 17 January 1974 samples taken up and downwind of a bleeding well both had radon concentrations of less than 0.05 pCi/l. On 2 February 1974 samples taken at equal distances (~75 ft) up and downwind of a well during performance testing had radon concentrations of less than 0.05 and 0.16±0.02 pCi/l respectively. On 10 March 1974. samples taken up and downwind of a well during performance testing both had radon concentrations of less than 0.05 pCi/l. In this case, the downwind sample was taken in the visible steam plume about 300 ft from the well. On 29 March 1974 samples taken up and downwind of a well during performance testing had radon concentrations of less than 0.1 and *0.25±0.03* pCi/l respectively. In this case, the downwind sample was taken in the visible steam plume about 100 ft from the well.

In some instances, within relatively small distances it is possible to detect the contribution of radon from steam wells. However, even the highest value measured in a steam plume 100 ft from a well (29 March 1974) was less than the average concentration of radon in air over continental areas which is about *0.3* pCi/l (see discussion in Chapter 2).

Related Studies--The study of radon at The Geysers power plants cited earlier (Mark Mathisen, P.G. & E., personal communication) included several measurements of ambient air. Ten of fifteen ambient air measurements, including several inside buildings, had reported radon concentrations of less than 0.01 pCi/l. The highest values were 0.20±0.03 pCi/l in air between a turbine building and cooling tower, and 0.21±0.02 pCi/l at a cooling tower.

Another study was performed at The Geysers to assess potential inhalation radiation exposure to workers (LFE Environmental, 1974)(. The measurements in this study were of radon daughters ($^{218}$Po, $^{214}$Bi, and $^{214}$Pb) collected by high-volume air samplers equipped with high particulate retention filter paper. Samples were collected in various :Locations ranging from directly in visible steam to several miles off-site. The results showed $^{218}$Po concentrations of 0.00 to 0.28 pCi/l, average 0.066 pCi/l; $^{214}$Bi concentrations of 0.01 to 0.11 pCi/l, average 0.060 pCi/l; and $^{214}$Pb concentrations of 0.03 to 0.13 pCi/l, average 0.068 pCi/l. These values are comparable to the results for radon measurements if it is assumed that the daughter products on particulates are in equilibrium with the radon.

Radon Emission from Soil--Radon flux with soil gas was measured at three locations in the mountain valley of The Geysers area where the developmental field was located. One measurement was made at the lower end of the valley (near hot spring), two measurements were made at one location midway up the valley in the vicinity of the wells, and one measurement was made on the ridge at the upper end of the valley. The results are presented in Table 18. The radon concentration buildup observed in the accumulator is shown in Figure 16.

The radon fluxes (in units of $10^{-5}$ pCi/cm$^{2}$-sec) were computed to be 1.3±0.1 at the lower end of the valley, 5.5±0.3 and 5.7±0.3 at the midpoint location, and 3.3±0.3 at the ridge. The average of the four values was about $4 \times 10^{-5}$ pCi/cm$^{2}$-sec. A reported average of worldwide measurements was $4.25 \times 10^{-5}$ pCi/cm$^{2}$-sec (Wilkening, et al., 1972). Thus, the soils in the valley appear to emit radon at rates in agreement with other reported values.

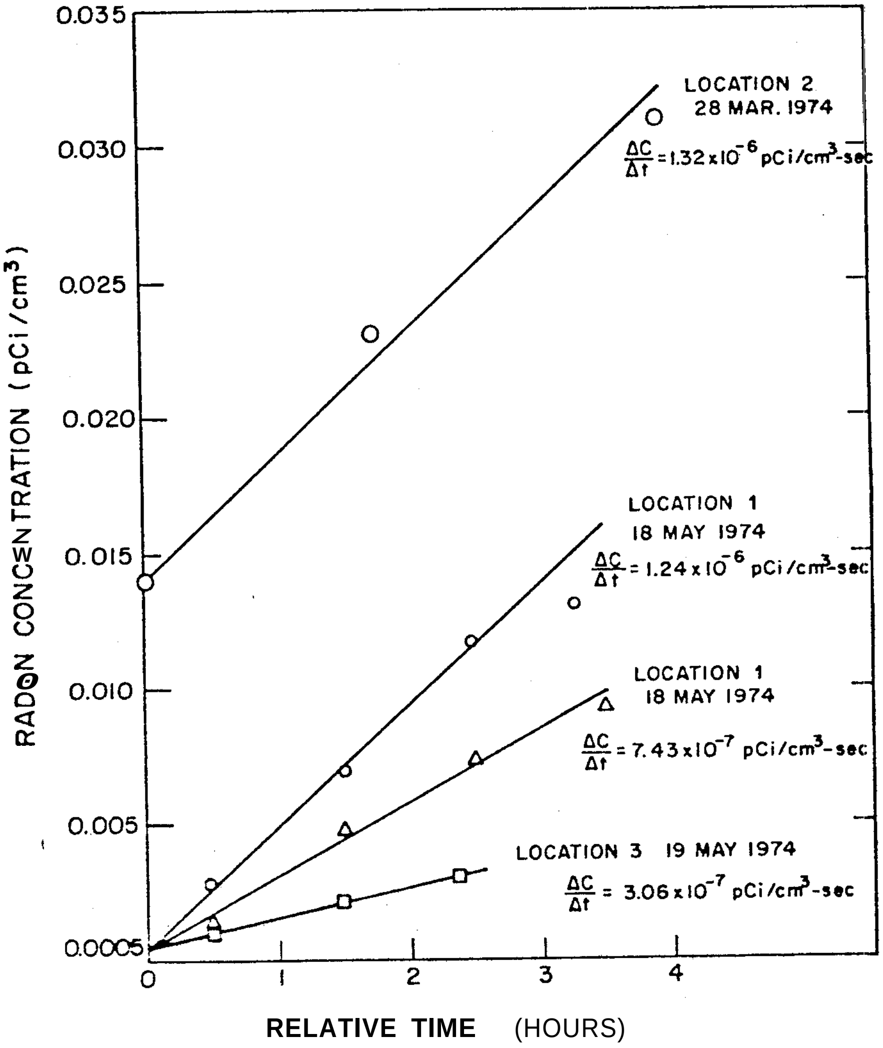

Figure 16. Radon buildup in accumulator for soil gas flux estimate.

# Chapter 5

# CONCLUSIONS AND RECOMMENDATIONS

## Radon as a Tracer in Geothermal Systems

*Basic Sampling & Measurement Techniques*--The sampling and measurement techniques devised and used in this study are suitable for most measurements of radon in fluid from geothermal wells and for environmental measurements. The general objectives of reliability, range of response, and simplicity of field operations were realized.

The evacuated cylinder sampling method is considered to be the most suitable means of obtaining samples from either steam or liquid producing wells. For the samples taken as part of this study, radon was easily measured with small errors of measurement.

Two principal areas of difficulty were experienced with the sampling technique. One was the small amount of noncondensable gases obtained in the samples and the other was the apparent inability to obtain representative samples from two-phase flow when flashing occurred in the wellbore (Magmamax #1). The small volumes of noncondensable gases collected in the samples often had partial pressures of only a few millimeters of mercury, a fraction of the vapor pressure of water at laboratory temperatures. This led to difficulty in accurately estimating the amount of noncondensables and in extracting noncondensables from the sample cylinders into a syringe by means of the peristalic pump for injection into the gas partitioner. A possible remedy to this problem is the application of limited condensation during sample collection. A suggested means of accomplishing limited induced condensation reproducibly is to support the sample cylinder from a spring scale while pouring cooling water over the cylinder. The scale would permit collection of samples with a predetermined amount of condensate. For example, samples with 1 lb of condensate, about 450 ml, would be 2 to 4 times as large as many of the steam well samples taken in this study. This would improve the accuracy of noncondensable gas volume measurements. The instrument used for noncondensable gas analysis should be changed. The inconsistencies noted in gas analyses were attributed to equipment malfunction as well as to the need to make two separate injections with different carrier gases. Furthermore, the equipment used was unable to measure some gases 'likely to be present, notably hydrogen sulphide and ammonia. Future work should consider the use of a good gas chromatograph which would increase the accuracy and the types of gases that could be measured. It would be desirable to continue the practice of measuring noncondensables in the same sample analyzed for radon in light of the results indicating rapid changes in noncondensable gas composition with time.

Sampling from two-phase flow situations will probably require the incorporation of additional equipment such as a small steam separator. Ellis, et al. (1968) have described such equipment for gas sampling from geothermal wells.

Future work involving the relationship of radon to gases or dissolved constituents should consider the use of stainless steel cylinders in order to avoid possible problems with corrosion reactions.

Potential Uses of Radon--This study undertook the development and testing of methods for measuring radon in geothermal fluids and their use in making actual field measurements as a basis for evaluating radon as a possible diagnostic tool for reservoir evaluation and to assess potential environmental problems. The basic feasibility of measuring radon in geothermal fluids has been established, but extensive additional work will be required to establish possible diagnostic uses for reservoir evaluation.

Only limited inference of reservoir parameters can be made from the data obtained in this study. For example, it is possible to estimate ranges of emanating power (E). Data from well East Elesa 6-2 can be used to make an estimate for the brine reservoir. It is assumed that the fluid sampled [illegible] the equilibrium conditions in the reservoir because [illegible] flow rate. Accordingly, equation 16 (Chapter 2) reduces to the relation $C = E/\phi$. Taking the average radon concentration of the four samples (Table 11) of 34 2 pCi/l, and correcting the liquid density to reservoir temperature conditions leads to a value for the ratio $E/\phi$ of 0.03 $pCi/cm^3$. This value could result from the following ranges of E and $\phi$ given as examples:

| $\phi$ | E ($pCi/cm^3$) |
|---|---|
| 0.05 | 0.0015 |
| 0.1 | 0.003 |
| 0.15 | 0.0045 |
| 0.2 | 0.006 |

The inferred range of plausible values for E may be compared to expected for Sedimentary rock. A typical radium content for sedimentary rock is 0.5 pCi/g, or about 1 $pCi/cm^3$. Typical emanation coefficients (ratio of radium able to release radon to fluids and total radium) for sedimentary materials range from 1 to 30 percent (Tokarev and Shcherbakov, 1956). These values would lead to E values of 0.01 to 0.3 $pCi/cm^3$. Thus the inferred values for E based on measurements are somewhat lower than the range expected for sedimentary rock with average radium content.

A similar estimate can be made from measurements made at the developmental field in The Geysers area. It is assumed that the steam obtained during the latter part of performance tests (Table 13) is representative of radioactive equilibrium in the reservoir because of the short flow times. Taking an average radon-condensate concentration of 3500 pCi/l, and correcting to the reservoir conditions of about 500 psia and 467°F leads to a value for $E/\phi$ of 0.06 $pCi/cm^3$. A range of values for $\phi$ can be assumed on the basis of other work indicating porosities of 0.5 to 1% as typical of the Franciscan graywacke (Ramey, 1974). The inferred value of $E/\phi$ could result from the following ranges of E and $\phi$ given as examples:

| $\phi$ | E ($pCi/cm^3$) |
|---|---|
| 0.001 | 0.00006 |
| 0.005 | 0.0003 |
| 0.01 | 0.0006 |
| 0.05 | 0.003 |

Thus, the probable range of E is lower than that estimated for the sedimentary rock. It would be desirable to obtain estimates of emanating power directly from samples of reservoir formation rock.

The possibility of using radon measurements to infer reservoir parameters $\phi$ or $\phi h$ by the method described in Chapter 2 (pages 30-31) can be anticipated based on data from the performance tests of well IV-D (Table 13). It is assumed that the wellhead parameters of pressure and temperature are approximately those of a steady-state flow. These parameters can be used to evaluate some of the terms in equation 17 (Chapter 2) for radial flow of compressible fluid. If the standard conditions are taken to be those at the wellhead, the equation can be expressed as:

$$C = \frac{E}{\phi} Kv$$

where $K = \frac{1}{\alpha}(1 + \frac{\omega}{2}\sqrt{\frac{\pi}{\alpha}})$, v is the specific volume of wellhead steam, and the remaining terms are as defined in Chapter 2. Evaluation of the term Kv and multiplying it by the value of $E/\phi$ computed earlier leads to a predicted value for C, the radon-condensate concentration. The parameters used in the calculation and the results are presented in Table 19.

Table 19

Predicted Radon Concentrations for Steady State Flow

| Test Identification | bleed | 3-27-74 @ 8 hr | 3-28-74 @ 8 hr | 3-29-74 @ 8 hr |
|---|---|---|---|---|
| Flow rate, lb/hr | ~5000 | 100,000 | 109,000 | 115,000 |
| $P_w$, psia | 470 | 206 | 147 | 82 |
| $T_w$, $^{\circ}F$ | 457 | 383 | 350 | 313 |
| $P_s$, psia | 485 | 485 | 480 | 475 |
| K | 0.99 | 0.49 | 0.32 | 0.14 |
| v, $ft^3/lb$ | 1.0 | 2.2 | 3.1 | 5.4 |
| Kv | 0.99 | 1.08 | 0.99 | 0.76 |
| C, pCi/l, predicted | 3500 | 3800 | 3500 | 2700 |
| C, pCi/l, measured | 180,000 | 3790 | 3200 | 3600 |

The predicted value of C for the bleeding rate does not take into account the buildup of noncondensables in the wellbore which was observed to occur. Thus, it is not surprising to see the large discrepancy in predicted and measured values. The predicted values of C based on the performance tests assume that steady state flow and radioactive equilibrium have occurred. Because tests only lasted a few hours, radioactive equilibrium was not achieved, and it is not surprising that the measured value for C for the 3-29-74 test is greater than predicted for equilibrium conditions. The interesting point is that the theory does predict a change in C at sufficiently high flow rates that should be measurable by the methodology developed for measuring radon. It will be necessary to conduct long term tests at different flow rates in order to confirm this prediction. If the measurements agree with theory, there may be some possibility of determining $\phi$ or $\phi h$ in geothermal reservoirs by measurement of radon.

The potential use of radon measurements to determine changes in surface area changes within reservoirs is not directly addressed by any of the results of this study. The fact that radon is present in readily measured amounts in geothermal fluids suggests that this potential use should be explored. Induced fracturing could affect either the emanating power or the porosity leading to changes in the $E/\phi$ ratio. Both effects could occur at the same time. Thus, it will be necessary to investigate the changes in both $E$ and $\phi$ as representative samples of rock are altered by either thermal stress, explosive shock or hydraulic fracturing. This should be a fruitful area of laboratory investigation, possibly utilizing the Stanford University Geothermal Simulation apparatus.

There is a possibility of utilizing measurements of radon during transient flow conditions while steady state flow and radioactive equilibrium conditions are being approached. This avenue has yet to be explored theoretically. Sakakura, et al. (1959) suggest that such an approach would be difficult because of the many hard-to-measure variables involved. The results of this study indicate that there will be difficult experimental problems as well, especially in the case of steam wells. The buildup of noncondensable gases in the wellbore due to steam condensation by heat losses would require the incorporation of modeling to account for the fractionation of steam and radon. It might be more fruitful initially to attempt modeling and measurement for liquid systems.

Because changes in radon concentrations in subsurface fluids have been noted as a possible precursor to seismic events (Hammond, 1973), this avenue should be pursued in relation to geothermal systems. Subsidence and induction of seismic activity may be an effect of withdrawal of large volumes of geofluids. Seismic studies have been conducted in geothermal settings and more are likely. Thus there may be opportunities for coordinated studies utilizing the results of radon measurements from geothermal wells.

Further Testing--The preliminary results of this study suggest certain types of experiments that might contribute to understanding the occurrence and behavior of radon in geothermal systems. The tests of two production wells (see Figures 13 and 14) indicated that the radon concentration in steam remained relatively constant over periods up to about 24 hours. However, there were variations from average values slightly larger than could be attributed to errors in measurement. It is not known whether these variations were due to changes in the composition of the sampled steam or to unidentified errors in the sampling and measurement methods. Accordingly, further long term tests are proposed. It would be desirable to sample a well flowing at a constant rate over periods of several days to several weeks using sampling intervals ranging fron minutes to days. This should permit good definition of the stability with time of radon concentrations in geothermal fluids. Such sampling coupled with better methods of measuring noncondensable gases should also permit better definition of the variation of such gases. Noncondensable gas volume and composition appeared to vary significantly and rapidly in the individual wells sampled in this study, even in situations where the radon-steam ratio remained relatively constant. Thus, it would be desirable to know whether the variations in noncondensable gases are real or more due to the difficulties experienced in their measurement.

Relationships of flow rates and radon concentrations in steam need to be explored more fully. Radon-condensate concentrations in samples obtained during production tests (e.g. Figures 11 and 12) did not appear to be significantly related to flow rate. The samples obtained from a production well at different flow rates exhibited slightly increased radon-condensate concentrations at higher flow rates--in contrast to the expectations of an inverse relation. However, neither of these types of tests were conducted for long enough times to permit radioactive equilibrium to be reached. Accordingly, it will be necessary to conduct a multiple flow rate test with sampling continued for sufficient time to permit radioactive equilibrium. This type of test could be an extension of the stability test suggested above. For example, the stability test could be conducted over about a two week period at one flow rate, and sampling continued at a second higher flow rate for another two week period. This should permit attainment of more than 90% of the radioactive equilibriun, and should provide an experimental check of the predicted change in radon concentration with flow rate. The two flow rates would have to be sufficiently different as to give predicted differences that would be distinguishable from established measurement errors and observed natural variations with time. The results from such a test could also be useful for evaluating transient flow models.

An important parameter in the theoretical models is the E/$\phi$ ratio. Accordingly it would be desirable to obtain suitable samples of actual reservoir formation rocks in order to measure their emanating power and porosity. Ideally, these measurements should be performed on core samples which preserve the integrity of the formation rock. Drill cuttings would permit only rough measurements because the surface area and porosity are altered. Cores would also be useful for laboratory experiments that would attempt to determine the changes in emanating power resulting from various types of fracturing.

The measurements of radon concentrations in steam determined in samples from wells at different locations and depths indicate that there may be significant inhomogeneity of radium bearing rock within reservoirs. Analysis of radon emanation from samples of reservoir rock from different wells and at different depths would permit characterization of the variation through a typical reservoir. This is essential to confirming the assumptions of uniform distribution which are the basis of the models. At a minimum, such measurements would permit definition of the inaccuracies in the models due to inhomogeneous distribution of emanating power.

### Radon as a Potential Pollutant

Actual environmental measurements of radon in the vicinity of geothermal operations reported in this study and by the other two studies summarized in Chapter *4* had concentrations less than the average of 0.3 pCi/l for air over continental areas. Thus, the contributions of radon from geothermal steam production are not presently producing effects that are distinguishable from naturally present radon.

An estimate of the radon release from a power plant utilizing geothermal steam can be based on the measurements of radon in steam made in this study. A radon-condensate concentration of 10,000 pCi/l is assumed as an average between the values measured for wells in the developmental and producing fields. For a 55 MW generating plant using steam at 20 lb/hr per kW of capacity the radon release would be 0.12 Ci/day. At this release rate, it would take some 250 such plants to equal the release of radon from natural gas use estimated at ***30*** **Ci/day** in Chapter 2.

A simple box model for atmospheric dilution can be used to estimate the increment of radon concentration due to the releases of radon from a power plant. A typical average wind speed of 5 mi/hr for mountain valleys is assumed (Hughes, 1973), as are a low inversion height of 0.2 mi and valley width of *3* mi. These values combined with the release rate of 0.12 Ci/day lead to a predicted concentration increment of *0.0004* pCi/l for radon in air. This is about 0.13% of the average natural concentration of radon over continental areas.

The soil flux values for radon reported in Chapter *4* can be used to make an estimate of power plant releases in comparison to the natural radon release. The average of the four reported flux measurements is about $4 \times 10^{-5}$ pCi/cm$^2$-sec, or about 0.09 Ci/mi$^2$-day. Thus the estimated power plant release of 0.12 Ci/day is equivalent to the natural release of radon from about **1.3** mi$^2$ of land area.

Thus, the environmental significance of radon release from power plants utilizing geothermal steam is small. Power plants utilizing liquids sampled in the vicinity of the Salton Sea would release even smaller amounts of radon. There would appear to be no basis for environmental impact concern over radon releases from geothermal energy utilization based on the results of this study. Additional survey measurements in other geothermal development areas would be justified to extend the documentation of limited environmental consequences.

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# APPENDIX A

## Growth of Decay Product Activity for $^{226}Ra$ and $^{222}Rn$ Parent Nuclides

(from Kirby, 1973)

# GROWTH OF DECAY PRODUCT ACTIVITY
## SERIES 4N + 2
## PARENT NUCLIDE: RA-226

| HRS | RA-226 1602.00 YRS | RN-222 3.824 DAY | PO-218 3.050 MIN | PB-214 26.800 MIN | BI-214 19.800 MIN | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|---|
| 0 | 1.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.00000 |
| 1 | 1.00000 | 0.00752 | 0.00698 | 0.00329 | 0.00158 | 1.01601 | 0.00481 |
| 2 | 1.00000 | 0.01499 | 0.01445 | 0.00988 | 0.00683 | 1.03626 | 0.01670 |
| 3 | 1.00000 | 0.02240 | 0.02187 | 0.01714 | 0.01372 | 1.05797 | 0.03085 |
| 4 | 1.00000 | 0.02976 | 0.02923 | 0.02449 | 0.02100 | 1.07997 | 0.04548 |
| 5 | 1.00000 | 0.03706 | 0.03653 | 0.03182 | 0.02833 | 1.10191 | 0.06015 |
| 6 | 1.00000 | 0.04430 | 0.04378 | 0.03911 | 0.03564 | 1.12371 | 0.07474 |
| 7 | 1.00000 | 0.05150 | 0.05097 | 0.04634 | 0.04289 | 1.14535 | 0.08922 |
| 8 | 1.00000 | 0.05863 | 0.05811 | 0.05351 | 0.05009 | 1.16683 | 0.10360 |
| 9 | 1.00000 | 0.06571 | 0.06520 | 0.06063 | 0.05724 | 1.18815 | 0.11787 |
| 10 | 1.00000 | 0.07274 | 0.07223 | 0.06770 | 0.06433 | 1.20930 | 0.13203 |
| 11 | 1.00000 | 0.07972 | 0.07922 | 0.07471 | 0.07137 | 1.23030 | 0.14608 |
| 12 | 1.00000 | 0.08665 | 0.08614 | 0.08168 | 0.07836 | 1.25114 | 0.16003 |
| 13 | 1.00000 | 0.09352 | 0.09302 | 0.08859 | 0.08530 | 1.27182 | 0.17388 |
| 14 | 1.00000 | 0.10034 | 0.09984 | 0.09544 | 0.09218 | 1.29235 | 0.18762 |
| 15 | 1.00000 | 0.10711 | 0.10662 | 0.10225 | 0.09901 | 1.31272 | 0.20125 |
| 16 | 1.00000 | 0.11383 | 0.11334 | 0.10901 | 0.10579 | 1.33294 | 0.21479 |
| 17 | 1.00000 | 0.12049 | 0.12001 | 0.11571 | 0.11252 | 1.35301 | 0.22822 |
| 18 | 1.00000 | 0.12711 | 0.12663 | 0.12236 | 0.11919 | 1.37293 | 0.24155 |
| 19 | 1.00000 | 0.13368 | 0.13320 | 0.12897 | 0.12582 | 1.39269 | 0.25479 |
| 20 | 1.00000 | 0.14020 | 0.13972 | 0.13552 | 0.13240 | 1.41231 | 0.26792 |
| 21 | 1.00000 | 0.14667 | 0.14620 | 0.14202 | 0.13893 | 1.43178 | 0.28095 |
| 22 | 1.00000 | 0.15309 | 0.15262 | 0.14848 | 0.14541 | 1.45110 | 0.29388 |
| 23 | 1.00000 | 0.15946 | 0.15900 | 0.15489 | 0.15184 | 1.47028 | 0.30672 |
| 24 | 1.00000 | 0.16578 | 0.16533 | 0.16125 | 0.15822 | 1.48932 | 0.31946 |
| 25 | 1.00000 | 0.17206 | 0.17161 | 0.16756 | 0.16455 | 1.50821 | 0.33211 |
| 26 | 1.00000 | 0.17829 | 0.17784 | 0.17382 | 0.17084 | 1.52696 | 0.34466 |
| 27 | 1.00000 | 0.18447 | 0.18402 | 0.18004 | 0.17708 | 1.54556 | 0.35711 |
| 28 | 1.00000 | 0.19061 | 0.19016 | 0.18621 | 0.18327 | 1.56403 | 0.36948 |
| 29 | 1.00000 | 0.19670 | 0.19626 | 0.19233 | 0.18941 | 1.58236 | 0.38175 |
| 30 | 1.00000 | 0.20274 | 0.20230 | 0.19841 | 0.19551 | 1.60055 | 0.39392 |
| 31 | 1.00000 | 0.20874 | 0.20831 | 0.20444 | 0.20157 | 1.61860 | 0.40601 |
| 32 | 1.00000 | 0.21470 | 0.21426 | 0.21042 | 0.20757 | 1.63652 | 0.41800 |
| 33 | 1.00000 | 0.22060 | 0.22018 | 0.21636 | 0.21354 | 1.65431 | 0.42991 |
| 34 | 1.00000 | 0.22647 | 0.22604 | 0.22226 | 0.21945 | 1.67195 | 0.44172 |
| 35 | 1.00000 | 0.23229 | 0.23187 | 0.22811 | 0.22533 | 1.68947 | 0.45345 |
| 36 | 1.00000 | 0.23807 | 0.23765 | 0.23392 | 0.23115 | 1.70686 | 0.46508 |
| 37 | 1.00000 | 0.24380 | 0.24338 | 0.23968 | 0.23694 | 1.72411 | 0.47663 |
| 38 | 1.00000 | 0.24949 | 0.24908 | 0.24541 | 0.24268 | 1.74123 | 0.48810 |
| 39 | 1.00000 | 0.25513 | 0.25473 | 0.25108 | 0.24838 | 1.75823 | 0.49947 |
| 40 | 1.00000 | 0.26074 | 0.26033 | 0.25672 | 0.25403 | 1.77510 | 0.51076 |

| HRS | RA-226 1602.00 YRS | RN-222 3.824 DAY | PO-218 3.050 MIN | PB-214 26.800 MIN | BI-214 19.800 MIN | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|---|
| 40 | 1.00000 | 0.26074 | 0.26033 | 0.25672 | 0.25403 | 1.77510 | 0.51076 |
| 42 | 1.00000 | 0.27182 | 0.27142 | 0.26786 | 0.26522 | 1.80845 | 0.53309 |
| 44 | 1.00000 | 0.28274 | 0.28234 | 0.27884 | 0.27623 | 1.84131 | 0.55509 |
| 46 | 1.00000 | 0.29349 | 0.29310 | 0.28965 | 0.28708 | 1.87367 | 0.57675 |
| 48 | 1.00000 | 0.30408 | 0.30370 | 0.30030 | 0.29777 | 1.90555 | 0.59809 |
| 50 | 1.00000 | 0.31452 | 0.31414 | 0.31079 | 0.30830 | 1.93694 | 0.61911 |
| 52 | 1.00000 | 0.32479 | 0.32442 | 0.32112 | 0.31867 | 1.96787 | 0.63982 |
| 54 | 1.00000 | 0.33492 | 0.33455 | 0.33130 | 0.32888 | 1.99834 | 0.66021 |
| 56 | 1.00000 | 0.34489 | 0.34453 | 0.34132 | 0.33894 | 2.02835 | 0.68030 |
| 58 | 1.00000 | 0.35471 | 0.35435 | 0.35120 | 0.34885 | 2.05790 | 0.70009 |
| 60 | 1.00000 | 0.36438 | 0.36403 | 0.36092 | 0.35862 | 2.08702 | 0.71958 |
| 62 | 1.00000 | 0.37391 | 0.37357 | 0.37050 | 0.36823 | 2.11570 | 0.73878 |
| 64 | 1.00000 | 0.38330 | 0.38296 | 0.37994 | 0.37770 | 2.14395 | 0.75769 |
| 66 | 1.00000 | 0.39254 | 0.39221 | 0.38924 | 0.38703 | 2.17177 | 0.77632 |
| 68 | 1.00000 | 0.40165 | 0.40132 | 0.39839 | 0.39622 | 2.19918 | 0.79467 |
| 70 | 1.00000 | 0.41062 | 0.41030 | 0.40741 | 0.40527 | 2.22618 | 0.81274 |
| 72 | 1.00000 | 0.41946 | 0.41914 | 0.41630 | 0.41419 | 2.25277 | 0.83054 |
| 74 | 1.00000 | 0.42816 | 0.42784 | 0.42505 | 0.42297 | 2.27896 | 0.84808 |
| 76 | 1.00000 | 0.43673 | 0.43642 | 0.43367 | 0.43162 | 2.30476 | 0.86535 |
| 78 | 1.00000 | 0.44518 | 0.44487 | 0.44216 | 0.44014 | 2.33018 | 0.88237 |
| 80 | 1.00000 | 0.45349 | 0.45319 | 0.45052 | 0.44854 | 2.35521 | 0.89913 |
| 82 | 1.00000 | 0.46169 | 0.46139 | 0.45876 | 0.45680 | 2.37987 | 0.91564 |
| 84 | 1.00000 | 0.46976 | 0.46947 | 0.46687 | 0.46495 | 2.40416 | 0.93190 |
| 86 | 1.00000 | 0.47771 | 0.47742 | 0.47486 | 0.47297 | 2.42808 | 0.94792 |
| 88 | 1.00000 | 0.48554 | 0.48525 | 0.48274 | 0.48087 | 2.45165 | 0.96370 |
| 90 | 1.00000 | 0.49325 | 0.49297 | 0.49049 | 0.48865 | 2.47486 | 0.97924 |
| 92 | 1.00000 | 0.50085 | 0.50057 | 0.49813 | 0.49632 | 2.49772 | 0.99455 |
| 94 | 1.00000 | 0.50833 | 0.50806 | 0.50565 | 0.50387 | 2.52024 | 1.00963 |
| 96 | 1.00000 | 0.51570 | 0.51543 | 0.51306 | 0.51131 | 2.54243 | 1.02448 |
| 98 | 1.00000 | 0.52296 | 0.52270 | 0.52036 | 0.51863 | 2.56428 | 1.03911 |
| 100 | 1.00000 | 0.53011 | 0.52985 | 0.52756 | 0.52585 | 2.58580 | 1.05352 |
| 102 | 0.99999 | 0.53716 | 0.53690 | 0.53464 | 0.53296 | 2.60700 | 1.06772 |
| 104 | 0.99999 | 0.54409 | 0.54384 | 0.54161 | 0.53996 | 2.62788 | 1.08170 |
| 106 | 0.99999 | 0.55093 | 0.55068 | 0.54849 | 0.54686 | 2.64845 | 1.09547 |
| 108 | 0.99999 | 0.55766 | 0.55742 | 0.55526 | 0.55365 | 2.66872 | 1.10904 |
| 110 | 0.99999 | 0.56429 | 0.56405 | 0.56192 | 0.56034 | 2.68867 | 1.12241 |
| 112 | 0.99999 | 0.57082 | 0.57059 | 0.56849 | 0.56693 | 2.70833 | 1.13557 |
| 114 | 0.99999 | 0.57726 | 0.57703 | 0.57496 | 0.57342 | 2.72770 | 1.14854 |
| 116 | 0.99999 | 0.58360 | 0.58337 | 0.58133 | 0.57982 | 2.74677 | 1.16131 |
| 118 | 0.99999 | 0.58984 | 0.58961 | 0.58761 | 0.58612 | 2.76556 | 1.17389 |
| 120 | 0.99999 | 0.59599 | 0.59577 | 0.59379 | 0.59232 | 2.78407 | 1.18628 |

# GROWTH OF DECAY PRODUCT ACTIVITY
## SERIES 4N + 2
## PARENT NUCLIDE: RA-226

| DAY | RA-226 1602.00 YRS | RN-222 3.824 DAY | PB-210 22.000 YRS | BI-210 5.010 DAY | PO-210 138.400 DAY | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|---|
| 0 | 1.00000 | 0.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.00000 |
| 1 | 1.00000 | 0.16578 | 0.00001 | 0.00000 | 0.00000 | 1.48932 | 0.31946 |
| 2 | 1.00000 | 0.30408 | 0.00003 | 0.00001 | 0.00000 | 1.90555 | 0.59809 |
| 3 | 1.00000 | 0.41946 | 0.00006 | 0.00001 | 0.00000 | 2.25277 | 0.83054 |
| 4 | 1.00000 | 0.51570 | 0.00010 | 0.00002 | 0.00000 | 2.54243 | 1.02448 |
| 5 | 0.99999 | 0.59599 | 0.00015 | 0.00003 | 0.00000 | 2.78407 | 1.18628 |
| 6 | 0.99999 | 0.66297 | 0.00020 | 0.00005 | 0.00000 | 2.98564 | 1.32128 |
| 7 | 0.99999 | 0.71884 | 0.00026 | 0.00008 | 0.00000 | 3.15380 | 1.43392 |
| 8 | 0.99999 | 0.76545 | 0.00032 | 0.00011 | 0.00001 | 3.29408 | 1.52791 |
| 9 | 0.99999 | 0.80433 | 0.00039 | 0.00014 | 0.00001 | 3.41110 | 1.60635 |
| 10 | 0.99999 | 0.83677 | 0.00046 | 0.00018 | 0.00001 | 3.50873 | 1.67180 |
| 11 | 0.99999 | 0.86383 | 0.00053 | 0.00022 | 0.00001 | 3.59016 | 1.72643 |
| 12 | 0.99999 | 0.88640 | 0.00061 | 0.00026 | 0.00001 | 3.65810 | 1.77202 |
| 13 | 0.99998 | 0.90523 | 0.00069 | 0.00031 | 0.00001 | 3.71477 | 1.81008 |
| 14 | 0.99998 | 0.92094 | 0.00077 | 0.00037 | 0.00001 | 3.76205 | 1.84186 |
| 15 | 0.99998 | 0.93405 | 0.00085 | 0.00043 | 0.00001 | 3.80149 | 1.86840 |
| 16 | 0.99998 | 0.94498 | 0.00093 | 0.00049 | 0.00002 | 3.83439 | 1.89056 |
| 17 | 0.99998 | 0.95410 | 0.00101 | 0.00055 | 0.00002 | 3.86184 | 1.90907 |
| 18 | 0.99998 | 0.96170 | 0.00109 | 0.00061 | 0.00002 | 3.88473 | 1.92455 |
| 19 | 0.99998 | 0.96805 | 0.00117 | 0.00068 | 0.00002 | 3.90383 | 1.93748 |
| 20 | 0.99998 | 0.97334 | 0.00126 | 0.00075 | 0.00003 | 3.91977 | 1.94830 |
| 21 | 0.99998 | 0.97776 | 0.00134 | 0.00082 | 0.00003 | 3.93306 | 1.95735 |
| 22 | 0.99997 | 0.98144 | 0.00143 | 0.00090 | 0.00004 | 3.94415 | 1.96493 |
| 23 | 0.99997 | 0.98452 | 0.00151 | 0.00097 | 0.00004 | 3.95340 | 1.97128 |
| 24 | 0.99997 | 0.98708 | 0.00160 | 0.00105 | 0.00005 | 3.96112 | 1.97660 |
| 25 | 0.99997 | 0.98922 | 0.00168 | 0.00112 | 0.00005 | 3.96756 | 1.98107 |
| 26 | 0.99997 | 0.99100 | 0.00177 | 0.00120 | 0.00006 | 3.97293 | 1.98482 |
| 27 | 0.99997 | 0.99249 | 0.00185 | 0.00128 | 0.00006 | 3.97741 | 1.98799 |
| 28 | 0.99997 | 0.99373 | 0.00194 | 0.00136 | 0.00007 | 3.98115 | 1.99065 |
| 29 | 0.99997 | 0.99476 | 0.00202 | 0.00144 | 0.00007 | 3.98427 | 1.99290 |
| 30 | 0.99996 | 0.99563 | 0.00211 | 0.00152 | 0.00008 | 3.98687 | 1.99481 |
| 31 | 0.99996 | 0.99635 | 0.00219 | 0.00160 | 0.00009 | 3.98904 | 1.99642 |
| 32 | 0.99996 | 0.99695 | 0.00228 | 0.00169 | 0.00010 | 3.99086 | 1.99780 |
| 33 | 0.99996 | 0.99745 | 0.00237 | 0.00177 | 0.00010 | 3.99237 | 1.99898 |
| 34 | 0.99996 | 0.99786 | 0.00245 | 0.00185 | 0.00011 | 3.99363 | 1.99999 |
| 35 | 0.99996 | 0.99821 | 0.00254 | 0.00194 | 0.00012 | 3.99469 | 2.00086 |
| 36 | 0.99996 | 0.99850 | 0.00262 | 0.00202 | 0.00013 | 3.99557 | 2.00161 |
| 37 | 0.99996 | 0.99874 | 0.00271 | 0.00210 | 0.00014 | 3.99631 | 2.00227 |
| 38 | 0.99996 | 0.99894 | 0.00279 | 0.00219 | 0.00015 | 3.99692 | 2.00285 |
| 39 | 0.99995 | 0.99911 | 0.00288 | 0.00227 | 0.00016 | 3.99744 | 2.00336 |
| 40 | 0.99995 | 0.99925 | 0.00297 | 0.00236 | 0.00017 | 3.99787 | 2.00381 |

| DAY | RA-226 1602.00 YRS | RN-222 3.824 DAY | B -210 2 .000 YRS | B I-210 5.010 DAY | PO-210 138.400 DAY | TOTAL ALPHA | TTAL BETA |
|---|---|---|---|---|---|---|---|
| 40 | 0.99995 | 0.99925 | 0.00297 | 0.00236 | 0.00017 | 3.99780 | 2.00381 |
| 41 | 0.99995 | 0.99937 | 0.00305 | 0.00244 | 0.00018 | 3.99823 | 2.00421 |
| 42 | 0.99995 | 0.99947 | 0.00314 | 0.00253 | 0.00019 | 3.99853 | 2.00458 |
| 43 | 0.99995 | 0.99955 | 0.00322 | 0.00261 | 0.0002[illegible] | 3.99878 | 2.004[illegible] |
| 44 | 0.99995 | 0.99961 | 0.00331 | 0.00270 | 0.00022 | 3.99900 | 2.00522 |
| 45 | 0.99995 | 0.99967 | 0.00340 | 0.00278 | 0.00023 | 3.99917 | 2.00550 |
| 46 | 0.99995 | 0.99972 | 0.00348 | 0.00287 | 0.00024 | 3.99933 | 2.0057[illegible] |
| 47 | 0.99994 | 0.99975 | 0.00357 | 0.00295 | 0.00026 | 3.99945 | 2.00602 |
| 48 | 0.99994 | 0.99979 | 0.00365 | 0.00304 | 0.00027 | 3.99956 | 2.00625 |
| 49 | 0.99994 | 0.99981 | 0.00374 | 0.00313 | 0.00029 | 3.99966 | 2.00648 |
| 50 | 0.99994 | 0.99983 | 0.00383 | 0.00321 | 0.00030 | 3.99973 | 2.0066[illegible] |
| 51 | 0.99994 | 0.99985 | 0.00391 | 0.00330 | 0.0003[illegible] | 3.99980 | 2.00690 |
| 52 | 0.99994 | 0.99987 | 0.00400 | 0.00338 | 0.00033 | 3.99986 | 2.00710 |
| 53 | 0.99994 | 0.99988 | 0.00408 | 0.00347 | 0.00035 | 3.9999[illegible] | 2.00730 |
| 54 | 0.99994 | 0.99989 | 0.004[illegible] | 0.00355 | 0.00036 | 3.99996 | 2.00709 |
| 55 | 0.99993 | 0.99990 | 0.00426 | 0.00364 | 0.0003[illegible] | 3.99999 | 2.0076[illegible] |
| 56 | 0.99993 | 0.99990 | 0.00434 | 0.00373 | 0.00039 | 4.00003 | 2.00786 |
| 57 | 0.99993 | 0.99991 | 0.00443 | 0.00381 | 0.0004[illegible] | 4.00006 | 2.00805 |
| 58 | 0.99993 | 0.99991 | 0.00451 | 0.00390 | 0.00043 | 4.00009 | 2.00823 |
| 59 | 0.99993 | 0.99992 | 0.00460 | 0.00398 | 0.00045 | 4.00012 | 2.00840 |
| 60 | 0.99993 | 0.99992 | 0.00468 | 0.00407 | 0.00046 | 4.00014 | 2.00858 |
| 61 | 0.99993 | 0.99992 | 0.00477 | 0.00415 | 0.00048 | 4.00016 | 2.00876 |
| 62 | 0.99993 | 0.99992 | 0.00486 | 0.00424 | 0.00050 | 4.00019 | 2.00893 |
| 63 | 0.99993 | 0.99992 | 0.00494 | 0.00433 | 0.00052 | 4.0002[illegible] | 2.009[illegible] |
| 64 | 0.99992 | 0.99992 | 0.00503 | 0.00441 | 0.00054 | 4.00023 | 2.0092[illegible] |
| 65 | 0.99992 | 0.99993 | 0.00511 | 0.00450 | 0.00056 | 4.00025 | 2.00945 |
| 66 | 0.99992 | 0.99993 | 0.00520 | 0.00458 | 0.00058 | 4.00027 | 2.00962 |
| 67 | 0.99992 | 0.99993 | 0.00529 | 0.00467 | 0.00060 | 4.00028 | 2.00979 |
| 68 | 0.99992 | 0.99993 | 0.00537 | 0.00476 | 0.00062 | 4.00030 | 2.00996 |
| 69 | 0.99992 | 0.99992 | 0.00546 | 0.00484 | 0.00064 | 4.00032 | 2.01014 |
| 70 | 0.99992 | 0.99992 | 0.00554 | 0.00493 | 0.00066 | 4.00034 | 2.0103[illegible] |
| 71 | 0.99992 | 0.99992 | 0.00563 | 0.00501 | 0.00068 | 4.00036 | 2.01048 |
| 72 | 0.99991 | 0.99992 | 0.00571 | 0.00510 | 0.00070 | 4.0003[illegible] | 2.01065 |
| 73 | 0.99991 | 0.99992 | 0.00580 | 0.00518 | 0.00073 | 4.00039 | 2.01082 |
| 74 | 0.99991 | 0.99992 | 0.00589 | 0.00527 | 0.00075 | 4.00041 | 2.01099 |
| 75 | 0.99991 | 0.99992 | 0.005[illegible]7 | 0.00536 | 0.00077 | 4.00043 | 2.011[illegible] |
| 76 | 0.99991 | 0.99992 | 0.00606 | 0.00544 | 0.00079 | 4.00045 | 2.01133 |
| 77 | 0.99991 | 0.99992 | 0.00614 | 0.00553 | 0.00082 | 4.00047 | 2.01150 |
| 78 | 0.99991 | 0.99992 | 0.00623 | 0.00561 | 0.00084 | 4.00049 | 2.01166 |
| 79 | 0.99991 | 0.99992 | 0.00631 | 0.00570 | 0.00087 | 4.00051 | 2.01183 |
| 80 | 0.99991 | 0.99991 | 0.00640 | 0.00579 | 0.00089 | 4.00053 | 2.01200 |

# GROWTH OF DECAY PRODUCT ACTIVITY
## SERIES 4N + 2
## PARENT NUCLIDE: RA-226

| DAY | RA-226 1602.00 YRS | RN-222 3.824 DAY | PB-210 22.000 YRS | BI-210 5.010 DAY | PO-210 138.400 DAY | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|---|
| 80 | 0.99991 | 0.99991 | 0.00640 | 0.00579 | 0.00089 | 4.00053 | 2.01200 |
| 81 | 0.99990 | 0.99991 | 0.00649 | 0.00587 | 0.00091 | 4.00055 | 2.01217 |
| 82 | 0.99990 | 0.99991 | 0.00657 | 0.00596 | 0.00094 | 4.00057 | 2.01234 |
| 83 | 0.99990 | 0.99991 | 0.00666 | 0.00604 | 0.00097 | 4.00059 | 2.01251 |
| 84 | 0.99990 | 0.99991 | 0.00674 | 0.00613 | 0.00099 | 4.00061 | 2.01268 |
| 85 | 0.99990 | 0.99991 | 0.00683 | 0.00621 | 0.00102 | 4.00063 | 2.01285 |
| 86 | 0.99990 | 0.99991 | 0.00691 | 0.00630 | 0.00104 | 4.00065 | 2.01302 |
| 87 | 0.99990 | 0.99991 | 0.00700 | 0.00638 | 0.00107 | 4.00068 | 2.01319 |
| 88 | 0.99990 | 0.99991 | 0.00709 | 0.00647 | 0.00110 | 4.00070 | 2.01336 |
| 89 | 0.99989 | 0.99990 | 0.00717 | 0.00656 | 0.00112 | 4.00072 | 2.01353 |
| 90 | 0.99989 | 0.99990 | 0.00726 | 0.00664 | 0.00115 | 4.00074 | 2.01369 |
| 91 | 0.99989 | 0.99990 | 0.00734 | 0.00673 | 0.00118 | 4.00077 | 2.01386 |
| 92 | 0.99989 | 0.99990 | 0.00743 | 0.00681 | 0.00121 | 4.00079 | 2.01403 |
| 93 | 0.99989 | 0.99990 | 0.00751 | 0.00690 | 0.00123 | 4.00081 | 2.01420 |
| 94 | 0.99989 | 0.99990 | 0.00760 | 0.00698 | 0.00126 | 4.00084 | 2.01437 |
| 95 | 0.99989 | 0.99990 | 0.00768 | 0.00707 | 0.00129 | 4.00086 | 2.01454 |
| 96 | 0.99989 | 0.99990 | 0.00777 | 0.00716 | 0.00132 | 4.00089 | 2.01471 |
| 97 | 0.99989 | 0.99990 | 0.00786 | 0.00724 | 0.00135 | 4.00091 | 2.01488 |
| 98 | 0.99988 | 0.99989 | 0.00794 | 0.00733 | 0.00138 | 4.00094 | 2.01505 |
| 99 | 0.99988 | 0.99989 | 0.00803 | 0.00741 | 0.00141 | 4.00096 | 2.01521 |
| 100 | 0.99988 | 0.99989 | 0.00811 | 0.00750 | 0.00144 | 4.00099 | 2.01538 |
| 101 | 0.99988 | 0.99989 | 0.00820 | 0.00758 | 0.00147 | 4.00101 | 2.01555 |
| 102 | 0.99988 | 0.99989 | 0.00828 | 0.00767 | 0.00150 | 4.00104 | 2.01572 |
| 103 | 0.99988 | 0.99989 | 0.00837 | 0.00776 | 0.00153 | 4.00106 | 2.01589 |
| 104 | 0.99988 | 0.99989 | 0.00846 | 0.00784 | 0.00156 | 4.00109 | 2.01606 |
| 105 | 0.99988 | 0.99989 | 0.00854 | 0.00793 | 0.00159 | 4.00112 | 2.01623 |
| 106 | 0.99987 | 0.99988 | 0.00863 | 0.00801 | 0.00163 | 4.00114 | 2.01640 |
| 107 | 0.99987 | 0.99988 | 0.00871 | 0.00810 | 0.00166 | 4.00117 | 2.01656 |
| 108 | 0.99987 | 0.99988 | 0.00880 | 0.00818 | 0.00169 | 4.00120 | 2.01673 |
| 109 | 0.99987 | 0.99988 | 0.00888 | 0.00827 | 0.00172 | 4.00123 | 2.01690 |
| 110 | 0.99987 | 0.99988 | 0.00897 | 0.00835 | 0.00176 | 4.00126 | 2.01707 |
| 111 | 0.99987 | 0.99988 | 0.00905 | 0.00844 | 0.00179 | 4.00128 | 2.01724 |
| 112 | 0.99987 | 0.99988 | 0.00914 | 0.00853 | 0.00182 | 4.00131 | 2.01741 |
| 113 | 0.99987 | 0.99988 | 0.00922 | 0.00861 | 0.00186 | 4.00134 | 2.01758 |
| 114 | 0.99987 | 0.99987 | 0.00931 | 0.00870 | 0.00189 | 4.00137 | 2.01774 |
| 115 | 0.99986 | 0.99987 | 0.00940 | 0.00878 | 0.00192 | 4.00140 | 2.01791 |
| 116 | 0.99986 | 0.99987 | 0.00948 | 0.00887 | 0.00196 | 4.00143 | 2.01808 |
| 117 | 0.99986 | 0.99987 | 0.00957 | 0.00895 | 0.00199 | 4.00146 | 2.01825 |
| 118 | 0.99986 | 0.99987 | 0.00965 | 0.00904 | 0.00203 | 4.00149 | 2.01842 |
| 119 | 0.99986 | 0.99987 | 0.00974 | 0.00912 | 0.00206 | 4.00152 | 2.01859 |
| 120 | 0.99986 | 0.99987 | 0.00982 | 0.00921 | 0.00210 | 4.00155 | 2.01876 |

| DAY | RA-226 1602.00 YRS | RN-222 3.824 DAY | PB-210 22.000 YRS | BI-210 5.010 DAY | PO-210 138.400 DAY | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|---|
| 120 | 0.99986 | 0.99987 | 0.00982 | 0.00921 | 0.00210 | 4.00155 | 2.01876 |
| 126 | 0.99985 | 0.99986 | 0.01033 | 0.00972 | 0.00232 | 4.00174 | 2.01977 |
| 132 | 0.99984 | 0.99985 | 0.01085 | 0.01023 | 0.00254 | 4.00194 | 2.02078 |
| 138 | 0.99984 | 0.99985 | 0.01136 | 0.01075 | 0.00278 | 4.00215 | 2.02179 |
| 144 | 0.99983 | 0.99984 | 0.01187 | 0.01126 | 0.00302 | 4.00236 | 2.02280 |
| 150 | 0.99982 | 0.99983 | 0.01238 | 0.01177 | 0.00327 | 4.00258 | 2.02380 |
| 156 | 0.99982 | 0.99983 | 0.01289 | 0.01228 | 0.00353 | 4.00281 | 2.02481 |
| 162 | 0.99981 | 0.99982 | 0.01340 | 0.01279 | 0.00380 | 4.00305 | 2.02582 |
| 168 | 0.99980 | 0.99981 | 0.01391 | 0.01330 | 0.00407 | 4.00330 | 2.02683 |
| 174 | 0.99979 | 0.99980 | 0.01442 | 0.01381 | 0.00435 | 4.00355 | 2.02783 |
| 180 | 0.99979 | 0.99980 | 0.01493 | 0.01432 | 0.00464 | 4.00381 | 2.02884 |
| 186 | 0.99978 | 0.99979 | 0.01544 | 0.01483 | 0.00494 | 4.00407 | 2.02984 |
| 192 | 0.99977 | 0.99978 | 0.01595 | 0.01534 | 0.00524 | 4.00435 | 2.03085 |
| 198 | 0.99977 | 0.99978 | 0.01646 | 0.01585 | 0.00554 | 4.00463 | 2.03185 |
| 204 | 0.99976 | 0.99977 | 0.01697 | 0.01636 | 0.00586 | 4.00491 | 2.03286 |
| 210 | 0.99975 | 0.99976 | 0.01748 | 0.01687 | 0.00617 | 4.00520 | 2.03386 |
| 216 | 0.99974 | 0.99975 | 0.01799 | 0.01738 | 0.00650 | 4.00549 | 2.03486 |
| 222 | 0.99974 | 0.99975 | 0.01849 | 0.01789 | 0.00683 | 4.00580 | 2.03586 |
| 228 | 0.99973 | 0.99974 | 0.01900 | 0.01839 | 0.00716 | 4.00610 | 2.03687 |
| 234 | 0.99972 | 0.99973 | 0.01951 | 0.01890 | 0.00750 | 4.00642 | 2.03787 |
| 240 | 0.99972 | 0.99973 | 0.02002 | 0.01941 | 0.00785 | 4.00673 | 2.03887 |
| 246 | 0.99971 | 0.99972 | 0.02052 | 0.01992 | 0.00820 | 4.00705 | 2.03987 |
| 252 | 0.99970 | 0.99971 | 0.02103 | 0.02042 | 0.00855 | 4.00738 | 2.04087 |
| 258 | 0.99969 | 0.99970 | 0.02154 | 0.02093 | 0.00891 | 4.00771 | 2.04187 |
| 264 | 0.99969 | 0.99970 | 0.02204 | 0.02144 | 0.00928 | 4.00804 | 2.04286 |
| 270 | 0.99968 | 0.99969 | 0.02255 | 0.02194 | 0.00964 | 4.00838 | 2.04386 |
| 276 | 0.99967 | 0.99968 | 0.02305 | 0.02245 | 0.01001 | 4.00873 | 2.04486 |
| 282 | 0.99967 | 0.99968 | 0.02356 | 0.02296 | 0.01039 | 4.00907 | 2.04586 |
| 288 | 0.99966 | 0.99967 | 0.02407 | 0.02346 | 0.01077 | 4.00942 | 2.04685 |
| 294 | 0.99965 | 0.99966 | 0.02457 | 0.02397 | 0.01115 | 4.00978 | 2.04785 |
| 300 | 0.99964 | 0.99965 | 0.02507 | 0.02447 | 0.01154 | 4.01014 | 2.04884 |
| 306 | 0.99964 | 0.99965 | 0.02558 | 0.02498 | 0.01193 | 4.01050 | 2.04984 |
| 312 | 0.99963 | 0.99964 | 0.02608 | 0.02548 | 0.01232 | 4.01086 | 2.05083 |
| 318 | 0.99962 | 0.99963 | 0.02659 | 0.02598 | 0.01272 | 4.01123 | 2.05183 |
| 324 | 0.99962 | 0.99963 | 0.02709 | 0.02649 | 0.01312 | 4.01161 | 2.05282 |
| 330 | 0.99961 | 0.99962 | 0.02759 | 0.02699 | 0.01352 | 4.01198 | 2.05381 |
| 336 | 0.99960 | 0.99961 | 0.02810 | 0.02749 | 0.01393 | 4.01236 | 2.05480 |
| 342 | 0.99960 | 0.99960 | 0.02860 | 0.02800 | 0.01434 | 4.01274 | 2.05579 |
| 348 | 0.99959 | 0.99960 | 0.02910 | 0.02850 | 0.01475 | 4.01312 | 2.05679 |
| 354 | 0.99958 | 0.99959 | 0.02960 | 0.02900 | 0.01517 | 4.01351 | 2.05778 |
| 360 | 0.99957 | 0.99958 | 0.03011 | 0.02950 | 0.01558 | 4.01390 | 2.05877 |

# GROWTH OF DECAY PRODUCT ACTIVITY
## SERIES 4N+ 2
## PARENT NUCLIDE: RN-222

| MIN | RN-222 3.824 DAY | PO-218 3.050 MIN | PB-214 26.800 MIN | BI-214 19.800 MIN | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|
| 0 | 1.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.00000 |
| 1 | 0.99987 | 0.20327 | 0.00271 | 0.00003 | 1.20318 | 0.00273 |
| 2 | 0.99975 | 0.36520 | 0.00998 | 0.00024 | 1.36519 | 0.01021 |
| 3 | 0.99962 | 0.49418 | 0.02077 | 0.00075 | 1.49456 | 0.02151 |
| 4 | 0.99950 | 0.59692 | 0.03422 | 0.00167 | 1.59808 | 0.03588 |
| 5 | 0.99937 | 0.67874 | 0.04968 | 0.00305 | 1.68117 | 0.05272 |
| 6 | 0.99925 | 0.74391 | 0.06661 | 0.00494 | 1.74810 | 0.07154 |
| 7 | 0.99912 | 0.79580 | 0.08459 | 0.00737 | 1.80230 | 0.09195 |
| 8 | 0.99899 | 0.83712 | 0.10330 | 0.01035 | 1.84647 | 0.11364 |
| 9 | 0.99887 | 0.87001 | 0.12247 | 0.01388 | 1.88276 | 0.13634 |
| 10 | 0.99874 | 0.89619 | 0.14191 | 0.01795 | 1.91289 | 0.15985 |
| 11 | 0.99862 | 0.91703 | 0.16144 | 0.02255 | 1.93820 | 0.18399 |
| 12 | 0.99849 | 0.93360 | 0.18095 | 0.02767 | 1.95976 | 0.20861 |
| 13 | 0.99836 | 0.94678 | 0.20035 | 0.03328 | 1.97842 | 0.23362 |
| 14 | 0.99824 | 0.95725 | 0.21954 | 0.03936 | 1.99485 | 0.25889 |
| 15 | 0.99811 | 0.96557 | 0.23849 | 0.04589 | 2.00957 | 0.28437 |
| 16 | 0.99799 | 0.97217 | 0.25714 | 0.05284 | 2.02300 | 0.30997 |
| 17 | 0.99786 | 0.97740 | 0.27547 | 0.06018 | 2.03545 | 0.33564 |
| 18 | 0.99774 | 0.98155 | 0.29345 | 0.06790 | 2.04719 | 0.36134 |
| 19 | 0.99761 | 0.98483 | 0.31106 | 0.07597 | 2.05641 | 0.38701 |
| 20 | 0.99749 | 0.98741 | 0.32830 | 0.08436 | 2.06926 | 0.41264 |
| 21 | 0.99736 | 0.98944 | 0.34515 | 0.09304 | 2.07985 | 0.43818 |
| 22 | 0.99723 | 0.99104 | 0.36162 | 0.10200 | 2.09028 | 0.46361 |
| 23 | 0.99711 | 0.99229 | 0.37771 | 0.11121 | 2.10061 | 0.48891 |
| 24 | 0.99698 | 0.99325 | 0.39341 | 0.12065 | 2.11089 | 0.51406 |
| 25 | 0.99686 | 0.99400 | 0.40874 | 0.13030 | 2.12116 | 0.53903 |
| 26 | 0.99673 | 0.99456 | 0.42369 | 0.14014 | 2.13144 | 0.56382 |
| 27 | 0.99661 | 0.99499 | 0.43827 | 0.15015 | 2.14175 | 0.58841 |
| 28 | 0.99648 | 0.99531 | 0.45249 | 0.16030 | 2.15209 | 0.61278 |
| 29 | 0.99636 | 0.99553 | 0.46635 | 0.17060 | 2.16249 | 0.63694 |
| 30 | 0.99623 | 0.99568 | 0.47987 | 0.18101 | 2.17293 | 0.66086 |
| 31 | 0.99611 | 0.99578 | 0.49304 | 0.19152 | 2.18341 | 0.68454 |
| 32 | 0.99598 | 0.99583 | 0.50587 | 0.20211 | 2.19393 | 0.70798 |
| 33 | 0.99585 | 0.99585 | 0.51838 | 0.21278 | 2.20449 | 0.73115 |
| 34 | 0.99573 | 0.99584 | 0.53058 | 0.22351 | 2.21507 | 0.75407 |
| 35 | 0.99560 | 0.99580 | 0.54245 | 0.23428 | 2.22568 | 0.77672 |
| 36 | 0.99548 | 0.99575 | 0.55403 | 0.24508 | 2.23631 | 0.79910 |
| 37 | 0.99535 | 0.99568 | 0.56531 | 0.25590 | 2.24694 | 0.82120 |
| 38 | 0.99523 | 0.99560 | 0.57629 | 0.26674 | 2.25757 | 0.84302 |
| 39 | 0.99510 | 0.99551 | 0.58700 | 0.27757 | 2.26819 | 0.86456 |
| 40 | 0.99498 | 0.99541 | 0.59743 | 0.28840 | 2.27879 | 0.88582 |

# GROWTH OF DECAY PRODUCT ACTIVITY
# SERIES 4N + 2
# PARENT NUCLIDE: RN-222

| MIN | RN-222 3.824 DAY | PO-218 3.050 MIN | PB-214 26.800 MIN | BI-214 19.800 MIN | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|
| 40 | 0.99498 | 0.99541 | 0.59743 | 0.28840 | 2.27879 | 0.88582 |
| 42 | 0.99473 | 0.99520 | 0.61749 | 0.30999 | 2.29992 | 0.92746 |
| 44 | 0.99448 | 0.99498 | 0.63652 | 0.33144 | 2.32090 | 0.96795 |
| 46 | 0.99423 | 0.99474 | 0.65459 | 0.35269 | 2.34167 | 1.00727 |
| 48 | 0.99398 | 0.99450 | 0.67173 | 0.37370 | 2.36218 | 1.04542 |
| 50 | 0.99373 | 0.99426 | 0.68800 | 0.39441 | 2.38240 | 1.08240 |
| 52 | 0.99348 | 0.99401 | 0.70343 | 0.41480 | 2.40229 | 1.11822 |
| 54 | 0.99323 | 0.99377 | 0.71807 | 0.43482 | 2.42181 | 1.15288 |
| 56 | 0.99298 | 0.99352 | 0.73196 | 0.45445 | 2.44095 | 1.18641 |
| 58 | 0.99273 | 0.99327 | 0.74514 | 0.47367 | 2.45967 | 1.21881 |
| 60 | 0.99248 | 0.99302 | 0.75765 | 0.49246 | 2.47796 | 1.25010 |
| 62 | 0.99223 | 0.99277 | 0.76951 | 0.51080 | 2.49580 | 1.28030 |
| 64 | 0.99198 | 0.99252 | 0.78076 | 0.52868 | 2.51318 | 1.30943 |
| 66 | 0.99173 | 0.99227 | 0.79143 | 0.54610 | 2.53010 | 1.33751 |
| 68 | 0.99148 | 0.99202 | 0.80154 | 0.56304 | 2.54654 | 1.36457 |
| 70 | 0.99123 | 0.99177 | 0.81114 | 0.57949 | 2.56250 | 1.39063 |
| 72 | 0.99098 | 0.99152 | 0.82024 | 0.59547 | 2.57798 | 1.41571 |
| 74 | 0.99073 | 0.99127 | 0.82887 | 0.61097 | 2.59297 | 1.43983 |
| 76 | 0.99048 | 0.99102 | 0.83705 | 0.62599 | 2.60749 | 1.46303 |
| 78 | 0.99023 | 0.99077 | 0.84481 | 0.64053 | 2.62153 | 1.48532 |
| 80 | 0.98998 | 0.99052 | 0.85216 | 0.65459 | 2.63510 | 1.50674 |
| 82 | 0.98973 | 0.99028 | 0.85913 | 0.66819 | 2.64820 | 1.52731 |
| 84 | 0.98948 | 0.99003 | 0.86573 | 0.68133 | 2.66084 | 1.54706 |
| 86 | 0.98923 | 0.98978 | 0.87199 | 0.69402 | 2.67303 | 1.56600 |
| 88 | 0.98898 | 0.98953 | 0.87793 | 0.70626 | 2.68477 | 1.58418 |
| 90 | 0.98873 | 0.98928 | 0.88355 | 0.71806 | 2.69608 | 1.60160 |
| 92 | 0.98849 | 0.98903 | 0.88887 | 0.72943 | Z.70695 | 1.61830 |
| 94 | 0.98824 | 0.98878 | 0.89391 | 0.74039 | 2.71741 | 1.63429 |
| 96 | 0.98799 | 0.98853 | 0.89869 | 0.75094 | 2.72746 | 1.64962 |
| 98 | 0.98774 | 0.98828 | 0.90321 | 0.76108 | 2.73711 | 1.66429 |
| 100 | 0.98749 | 0.98803 | 0.90750 | 0.77084 | 2.74637 | 1.67833 |
| 102 | 0.98724 | 0.98779 | 0.91155 | 0.78022 | 2.75525 | 1.69176 |
| 104 | 0.98699 | 0.98754 | 0.91539 | 0.78924 | 2.76377 | 1.70461 |
| 106 | 0.98675 | 0.98729 | 0.91902 | 0.79789 | 2.77193 | 1.71690 |
| 108 | 0.98650 | 0.98704 | 0.92245 | 0.80620 | 2.77974 | 1.72865 |
| 110 | 0.98625 | 0.98679 | 0.92570 | 0.81417 | 2.78722 | 1.73987 |
| 112 | 0.98600 | 0.98654 | 0.92878 | 0.82182 | 2.79437 | 1.75059 |
| 114 | 0.98575 | 0.98629 | 0.93168 | 0.82915 | 2.80120 | 1.76083 |
| 116 | 0.98550 | 0.98605 | 0.93443 | 0.83618 | 2.80774 | 1.77061 |
| 118 | 0.98526 | 0.98580 | 0.93703 | 0.84292 | 2.81397 | 1.77994 |
| 120 | 0.98501 | 0.98555 | 0.93948 | 0.84936 | 2.81993 | 1.78884 |

| HRS | RN-222 3.824 DAY | PO-218 3.050 MIN | PB-214 26.800 MIN | BI-214 19.800 MIN | TOTAL ALPHA | TOTAL BETA |
|---|---|---|---|---|---|---|
| 0 | 1.00000 | 0.00000 | 0.00000 | 0.00000 | 1.00000 | 0.00000 |
| 1 | 0.99248 | 0.99302 | 0.75765 | 0.49246 | 2.47796 | 1.25010 |
| 2 | 0.98501 | 0.98555 | 0.93948 | 0.84936 | 2.81993 | 1.78884 |
| 3 | 0.97760 | 0.97813 | 0.97214 | 0.95134 | 2.90708 | 1.92348 |
| 4 | 0.97024 | 0.97077 | 0.97324 | 0.97106 | 2.91208 | 1.94430 |
| 5 | 0.96294 | 0.96347 | 0.96770 | 0.96992 | 2.89634 | 1.93763 |
| 6 | 0.95570 | 0.95622 | 0.96080 | 0.96399 | 2.87591 | 1.92480 |
| 7 | 0.94851 | 0.94903 | 0.95365 | 0.95704 | 2.85457 | 1.91070 |
| 8 | 0.94137 | 0.94189 | 0.94649 | 0.94990 | 2.83316 | 1.89641 |
| 9 | 0.93429 | 0.93480 | 0.93938 | 0.94276 | 2.81185 | 1.88216 |
| 10 | 0.92726 | 0.92777 | 0.93231 | 0.93567 | 2.79070 | 1.86801 |
| 11 | 0.92028 | 0.92079 | 0.92529 | 0.92863 | 2.76970 | 1.85396 |
| 12 | 0.91335 | 0.91386 | 0.91833 | 0.92165 | 2.74886 | 1.84001 |
| 13 | 0.90648 | 0.90698 | 0.91142 | 0.91471 | 2.72818 | 1.82617 |
| 14 | 0.89966 | 0.90016 | 0.90456 | 0.90783 | 2.70765 | 1.81243 |
| 15 | 0.89289 | 0.89338 | 0.89776 | 0.90100 | 2.68728 | 1.79880 |
| 16 | 0.88617 | 0.88666 | 0.89100 | 0.89422 | 2.66706 | 1.78527 |
| 17 | 0.87951 | 0.87999 | 0.88430 | 0.88749 | 2.64699 | 1.77184 |
| 18 | 0.87289 | 0.87337 | 0.87765 | 0.88082 | 2.62708 | 1.75851 |
| 19 | 0.86632 | 0.86680 | 0.87104 | 0.87419 | 2.60731 | 1.74529 |
| 20 | 0.85980 | 0.86028 | 0.86449 | 0.86761 | 2.58769 | 1.73216 |
| 21 | 0.85333 | 0.85380 | 0.85798 | 0.86108 | 2.56822 | 1.71913 |
| 22 | 0.84691 | 0.84738 | 0.85153 | 0.85460 | 2.54890 | 1.70620 |
| 23 | 0.84054 | 0.84100 | 0.84512 | 0.84817 | 2.52972 | 1.69336 |
| 24 | 0.83422 | 0.83468 | 0.83876 | 0.84179 | 2.51069 | 1.68063 |
| 25 | 0.82794 | 0.82839 | 0.83245 | 0.83546 | 2.49179 | 1.66798 |
| 26 | 0.82171 | 0.82216 | 0.82619 | 0.82917 | 2.47305 | 1.65544 |
| 27 | 0.81553 | 0.81598 | 0.81997 | 0.82293 | 2.45444 | 1.64299 |
| 28 | 0.80939 | 0.80984 | 0.81380 | 0.81674 | 2.43597 | 1.63063 |
| 29 | 0.80330 | 0.80374 | 0.80768 | 0.81060 | 2.41764 | 1.61836 |
| 30 | 0.79726 | 0.79770 | 0.80160 | 0.80450 | 2.39945 | 1.60619 |
| 31 | 0.79126 | 0.79169 | 0.79557 | 0.79844 | 2.38140 | 1.59411 |
| 32 | 0.78530 | 0.78574 | 0.78958 | 0.79244 | 2.36348 | 1.58212 |
| 33 | 0.77940 | 0.77982 | 0.78364 | 0.78647 | 2.34570 | 1.57022 |
| 34 | 0.77353 | 0.77396 | 0.77775 | 0.78056 | 2.32805 | 1.55841 |
| 35 | 0.76771 | 0.76813 | 0.77190 | 0.77468 | 2.31053 | 1.54669 |
| 36 | 0.76194 | 0.76235 | 0.76609 | 0.76885 | 2.29315 | 1.53506 |
| 37 | 0.75620 | 0.75662 | 0.76032 | 0.76307 | 2.27589 | 1.52351 |
| 38 | 0.75051 | 0.75093 | 0.75460 | 0.75733 | 2.25877 | 1.51205 |
| 39 | 0.74487 | 0.74528 | 0.74893 | 0.75163 | 2.24177 | 1.50068 |
| 40 | 0.73926 | 0.73967 | 0.74329 | 0.74597 | 2.22491 | 1.48939 |

# APPENDIX B

## Sample Data Sheet and Calculations

# RADON ANALYSIS **RECORD** SHEET

SAMPLE: LOCATION _______ DATE _________ TIME ______ $(t_s)$ BOTTLE # ___

ANALYSIS: DATE _______ TEMPERATURE _______

PRESSURE _____

| | MANOMETER<br>LEFT | MANOMETER<br>RIGHT | ABSOLUTE | |
|---|---|---|---|---|
| ATMOSPHERIC | _____ | _____ | _______ | |
| SAMPLE PRIOR TO PROCESSING | _____ | _____ | _______ | |
| $H_2O$ VAPOR PRESSURE | | | _______ | |
| ____________ | _____ | _____ | _______ | |
| ____________ | _____ | _____ | _______ | |
| PRESSURE @ START OF FLOW | _____ | _____ | _______ | $(p_i)$ |
| END OF FLOW | _____ | _____ | _______ | $(p_f)$ |

**LIQUID** VOLUME _______

FLOW INTO CONCENTRATION SYSTEM: START _____ END _____ RATE _____

FIRST FLUSH _____ AM/PM$(t_o)$ FLASH # ____

___FLUSH _____ AM/PM FLASK BACKGROUND ______________________

COUNT DATA

| START COUNT$(t_c)$ | COUNT LENGTH | TOTAL COUNT | $t_o - t_c$ | α | dpm @ $t_o$ | BACKGROUND | NET dpm |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

DECAY TIME $(t_o - t_s)$ = __d _____h ___m = _____h

DECAY FACTOR (d.f.) $e^{-0.0075526(t_o - t_s)}$ = ______

SAMPLE FRACTION ANALYZED (s.f.) $\frac{P_i - P_f}{P_i}$ = __________

RADON @ TIME OF SAMPLING = $\frac{\text{dpm}}{(\text{eff.})(2.22)(\text{d.f.})(\text{s.f.})}$ = ____________________

= __________ = __________

# RADON ANALYSIS **RECORD** SHEET

SAMPLE: LOCATION XXX DATE 3/29/74 TIME 13:30 ($t_s$) BOTTLE # 16

ANALYSIS: DATE 4/3/74 TEMPERATURE 22.6°C

PRESSURE DATA

| | MANOMETER | | |
|---|---|---|---|
| | LEFT | RIGHT | ABSOLUTE |
| ATMOSPHERIC | 101.5 | 867.0 | 765.5±2 |
| SAMPLE PRIOR TO PROCESSING | 114.5 | 855.0 | 25.0±2 |
| $H_2O$ VAPOR PRESSURE | | | 20.6±0.4 |
| Pressure of Non-Condensable Gases | | | 4.4±2.9 |
| | | | |
| PRESSURE @ START OF FLOW | 500 | 467 | 798.5±2 ($P_i$) |
| END OF FLOW | 258 | 704 | 319.5±2 ($P_f$) |

LIQUID VOLUME 111±2 ml

FLOW INTO CONCENTRATION SYSTEM: START 12:48 END 12:53 RATE

FIRST FLUSH 13:18AM/PM ($t_o$) FLASK # 1215

4th FLUSH 13:27AM/PM FLASK BACKGROUND 6 counts/30 **min** = 0.2±0.1 cpm

COUNT DATA

| START COUNT ($t_c$) | COUNT LENGTH | TOTAL COUNT | $t_o - t_c$ | α | dpm @ $t_o$ | BACKGROUND | NET dpm |
|---|---|---|---|---|---|---|---|
| 14:46 | 10 | 4398 | 88 | 2.71 | 162.3 | 0.1 | 162.2±1.51% |
| | | | | | | | |
| | | | | | | | |

DECAY TIME ($t_o - t_s$) = A d 23 h 48 m = 119.8h

DECAY FACTOR $e^{-0.0075526}$ ($t_o - t_s$) = 0.4046
(d.f.)

SAMPLE FRACTION ANALYZED $\frac{P_i - P_f}{P_i}$ = .5999±0.68%
(s.f.)

RADON @ TIME OF SAMPLING $= \frac{\text{dpm}}{(\text{eff.})(2.22)(\text{d.f.})(\text{s.f.})} = \frac{162.2}{(0.8)\ (2.22)\ (0.4046)\ (0.5999)}$

= 376.3±3.43% = 376±13pCi

Efficiency = 0.80±3.0%
(eff.)

*Background = $\frac{0.2}{2.71}$ ≃ 0.1 to account for α factor applied to gross count rate

## Calculations

### Volume of Non Condensable Gases

$$(\text{Tank Volume} - \text{Liquid Volume})\left(\frac{\text{NC Gas Pressure}}{760}\right)\left(\frac{273}{\text{NC Gas Temp.}}\right)$$

$$(4710 - 111)\left(\frac{4.4}{760}\right)\left(\frac{273}{295.6}\right) = 24.6 \pm 65\%$$

$$\text{or } 25 \pm 16 \text{ cm}^3$$

### Volume of $CO_2$

Amount as gas = (Volume of Gas)(Volume fraction $CO_2$)

$$= (24.6 \pm 65\%)(0.587 \pm 10\%) = 14.4 \pm 66\%$$

\+ Amount Dissolved = (NC Gas Pressure)(Correction Factor)(100's of ml $H_2O$)(Vol. Fraction $CO_2$)

$$= (4.4 \pm 65\%)(0.093)(1.11)(0.587 \pm 10\%) = 0.27 \pm 66\%$$

Total

$$14.67 \text{ cm}^3 \pm 66\%$$

$$\text{or } 15 \pm 10 \text{ cm}^3$$

### Concentration of Radon

Condensate: $$\frac{(376.3 \pm 3.43\%)}{(0.111 \mp 2\%)} = 3390 \pm 3.97\%$$

$$\text{or } 3390 \pm 140 \text{ pCi/l}$$

$CO_2$: $$\frac{(376.3 \mp 3.43\%)}{(.01467 \mp 65\%)} = 25650 \pm 65.1\%$$

$$\text{or } 26000 \pm 17000 \text{ pCi/l}$$