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RADON FLUX MEASUREMENTS ON GARDINIER AND ROYSTER PHOSPHOGYPSUM PILES NEAR TAMPA AND MULBERRY, FLORIDA

Prepared for
U.S. Environmental Protection Agency
Eastern Environmental Radiation Facility
Montgomery, Alabama
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J. N. Hartley
H. D. Freeman

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Pacific Northwest Laboratory
Richland, Washington 99352

ABSTRACT

As part of the planned Environmental Protection Agency (EPA) radon flux monitoring program for the Florida phosphogypsum piles, Pacific Northwest Laboratory (PNL), under contract to the EPA, constructed 50 large-area passive radon collection devices and demonstrated their use at two phosphogypsum piles near Tampa and Mulberry, Florida. The passive devices were also compared to the PNL large-area flow-through system.

The main objectives of the field tests were to demonstrate the use of the large-area passive radon collection devices to EPA and PEI personnel and to determine the number of radon flux measurement locations needed to estimate the average radon flux from a phosphogypsum pile.

This report presents the results of the field test, provides recommendations for long-term monitoring, and includes a procedure for making the radon flux measurements.

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INTRODUCTION

As part of the planned Environmental Protection Agency (EPA) radon flux monitoring program for the Florida phosphogypsum piles, Pacific Northwest Laboratory (PNL),[(a)] under contract to the EPA, constructed 50 large-area passive radon collection devices and demonstrated their use at two Florida phosphogypsum piles. The passive radon collection devices were tested and evaluated over a two-week period (April 29 to May 10, 1985) at the Gardinier and Royster phosphogypsum piles near Tampa and Mulberry, Florida, respectively. The passive devices were also compared to the PNL large-area flow-through system.

The main objectives of the field tests were to demonstrate the use of the large-area passive radon collection devices to EPA and PEI personnel and to determine the number of radon flux measurements locations needed to estimate the average radon flux from a phosphogypsum pile. Specific objectives were:

- to demonstrate and evaluate the use of the large (10-in.-diameter) activated charcoal radon collectors and compare them to the PNL flow-through system
- to obtain sufficient radon flux data to determine the spacial distribution of radon flux from the piles using 50 radon collectors
- to evaluate the large-area passive radon collectors on a thin source of phosphogypsum by comparing the measured versus calculated radon flux.

Originally, two inactive phosphogypsum piles were to be selected by EPA personnel for investigation of the spacial variability of radon flux. However, due to accessibility constraints, one active pile (Gardinier) and one inactive pile (Royster) were selected for field testing. These two field test sites were selected to represent somewhat typical conditions that exist on all active and inactive phosphogypsum piles. Arrangements to make measurements on these piles were made by PEI personnel.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

This report presents the results of the field test, provides recommendations for long-term monitoring, and describes a procedure for making the radon flux measurements.

METHOD

MEASURING RADON FLUX USING LARGE-AREA COLLECTORS

The method used to make radon flux measurements involves absorption of radon on activated charcoal in a large-area collector. This method, with many different geometries of collectors, has been used extensively since the publication of the paper by Countess (1976). The radon collector is placed on the surface of the material to be measured and is allowed to collect radon for a time period of up to 24 hours. The radon collected on the charcoal is then measured by gamma spectroscopy.

The PNL method differs slightly from other published methods in that a much larger area collector is used (Figures 1 and 2). The 0.052-m^2 collector is fabricated from a 10-in.-dia PVC end cap used for irrigation systems. The end cap is very rugged, therefore ideal for field use. The design of the collector, as shown in Figure 1, minimizes the space between the surface of the material being measured and the activated charcoal in the collector. This air gap must be minimized to obtain a valid radon flux measurement.

The collector consists of the PVC end cap, spacer pads, charcoal distribution grid, a retainer pad with screen, and a steel retainer spring (Figure 2). Approximately 170 grams of activated charcoal is spread in the distribution grid. The retainer pad is placed over the charcoal and held in place by the retainer spring.

The collectors are deployed by firmly twisting the end cap into the surface of the material to be measured. The deployment location and time are recorded in a notebook. After ~24 hours of exposure, the collectors are picked up and the time is recorded in the notebook. The activated charcoal is removed from the collector by removing the retaining spring and pad from the collector and dumping the charcoal into a large bowl. The charcoal is then placed and sealed in plastic containers ("cottage-cheese cartons" or equivalent) supplied by the EPA. The radon collected on the charcoal is allowed to equilibrate for 4 hours before counting to allow the ingrowth of radon daughters.

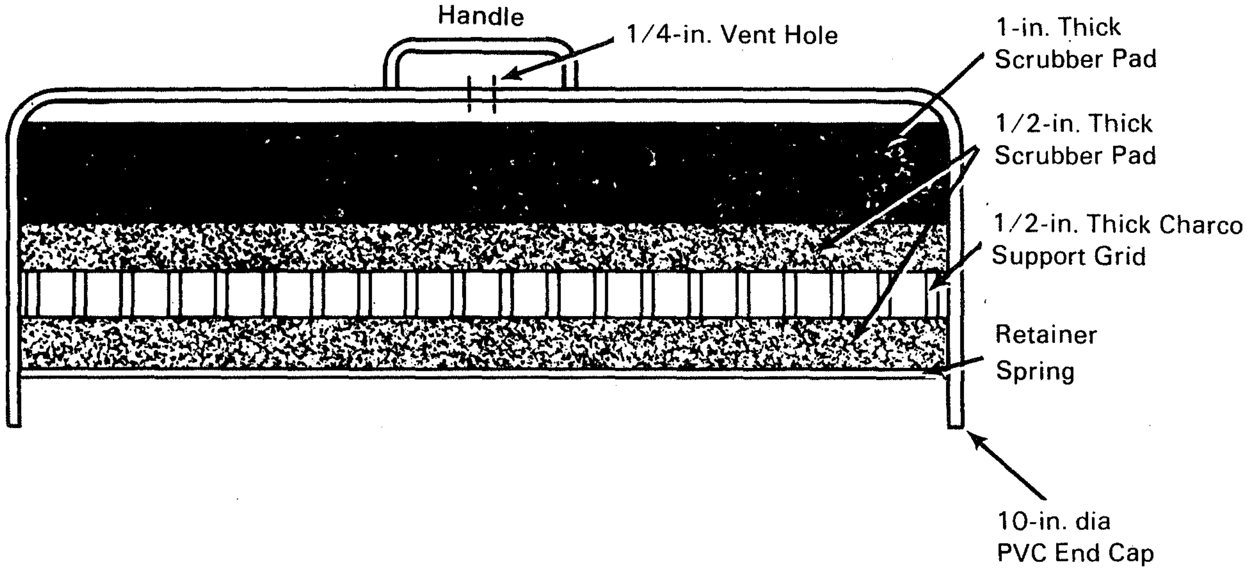


FIGURE 1. Large-Area Radon Collector

The amount of radon sorbed on the activated charcoal is determined by gamma spectroscopy. The gamma spectroscopy system used in this study consisted of a NaI(Tl) crystal, photomultiplier tube, amplifier, and scaler. The 609-keV ^{214}Bi radon decay product peak is used to quantify the radon on the charcoal. A National Bureau of Standards (NBS)-traceable standard of ^{226}Ra sorbed on charcoal in a "cottage-cheese carton" is counted at least once a day to determine the counting system's efficiency. A container of unexposed charcoal is also counted each day to determine the background. The radon flux is calculated from the net counts, collector area, exposure time, and counting system efficiency. A detailed procedure for preparing and deploying the collectors and calculating the radon flux is presented in Appendix A.

This method of radon flux measurement involves two basic assumptions. First, it is assumed that the charcoal is 100% efficient in collecting radon. For short time periods (<36 hours) this assumption is considered valid (Hartley et. al 1983). The charcoal may not be 100% efficient, however, if longer exposure times are used. The main factor affecting the efficiency of charcoal for radon collection is temperature.

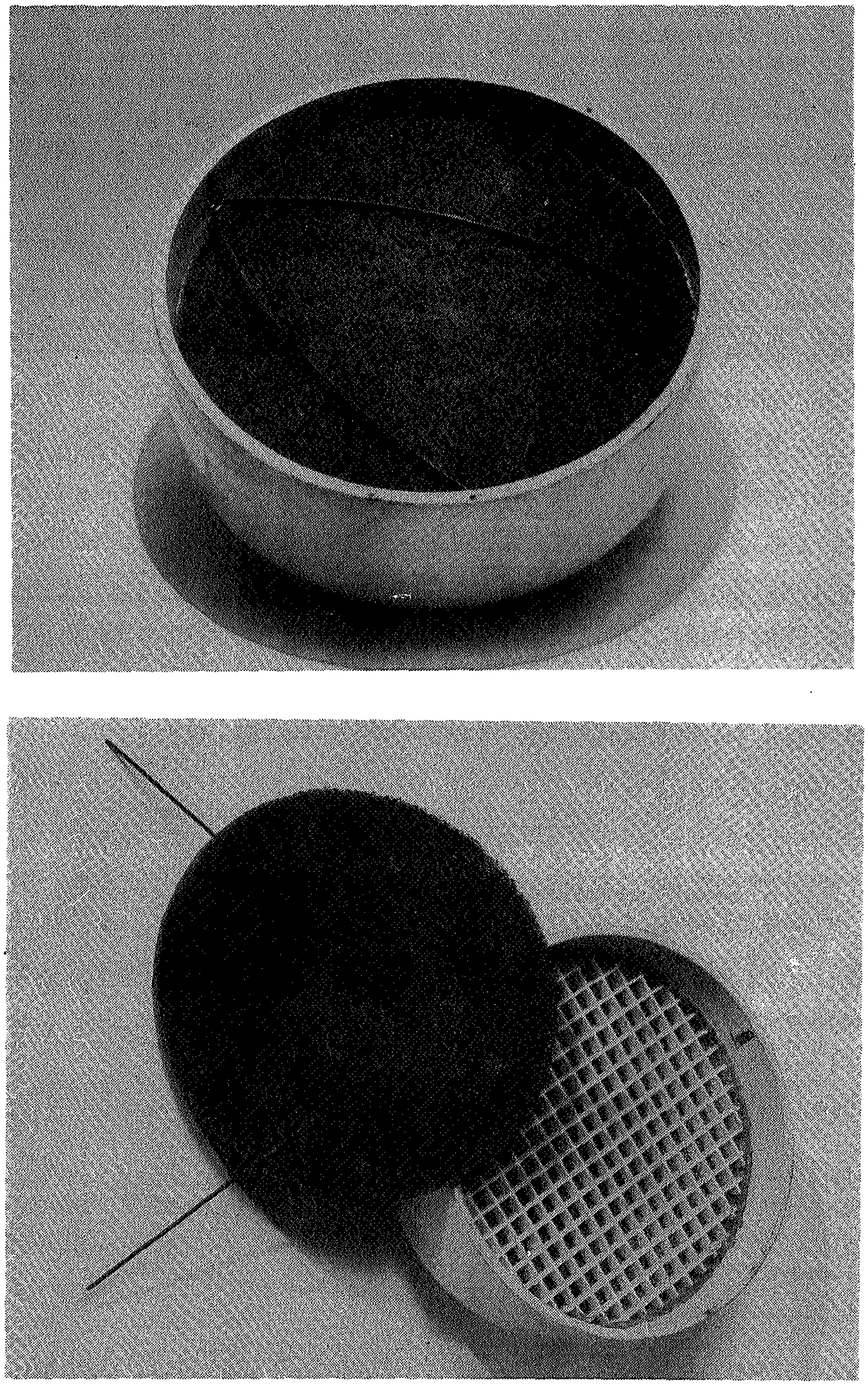


FIGURE 2. Components of Large-Area Radon Collector

Longer exposure times can be used in the winter than in the summer. Twenty-four hours is a conservative estimate of a valid exposure time for any time of year.

The second assumption is that the radon flux being measured is constant over the exposure period. Although it is known that this condition is rarely, if ever, met, the errors introduced are relatively small.

DETERMINING THE NUMBER OF LOCATIONS TO SAMPLE ON EACH PHOSPHOGYPSUM PILE

To estimate a statistically valid annual average radon flux for a phosphogypsum pile, the proper number of locations on the pile must be measured. The number of measurements needed to define the annual average flux depends on the homogeneity of the pile and the desired precision of the estimate. A homogenous pile requires fewer samples than a nonhomogenous pile. Standard statistical techniques (Holloway 1981) can be used to estimate the number of samples needed to estimate an average for a given error limit and uncertainty. The basic formula used to estimate the number of samples is:

$$\frac{\tau(n)\ s}{\sqrt{n}} < (\text{error})\bar{x} \tag{1}$$

where $\tau(n)$ is the students-τ distribution

s = measured standard deviation of the radon flux from the pile

$\bar{x}$ = measured mean of the radon flux from the pile

error = allowable error (expressed as a fraction)

n = number of samples.

This equation can be rearranged to give the error as a function of $\bar{x}$, s, n, and $\tau(n)$.

$$\text{error} \geq \frac{\tau(n)\ s}{\bar{x}\ \sqrt{n}} \tag{2}$$

For sample numbers greater than 30, $\tau(n)$ can be assumed to be 1.7. However, for sample numbers less than 30 where the students-τ distribution is nonlinear the actual students-τ distribution should be used.

Equation 2 was used to estimate the errors in the estimate of the radon flux average for the Gardinier and Royster phosphogypsum piles. The Royster pile was divided into active and inactive regions for the analysis. A confidence interval of 90% was used. Results of this analysis are presented in Figure 3. From this figure, it can be seen that approximately 28 samples are needed for the Gardinier pile in order to have a 25% error in the estimate of the average radon flux. The Royster pile, on the other hand, would require 12 and 93 samples for the active and inactive portions of the piles, respectively. This same analysis can be easily performed for other confidence intervals by using the appropriate students-τ distribution. A larger confidence interval (i.e., α = 0.025, 95% confidence) would necessitate more samples, while a smaller confidence interval (i.e., α = 0.1, 80% confidence) would require fewer samples.

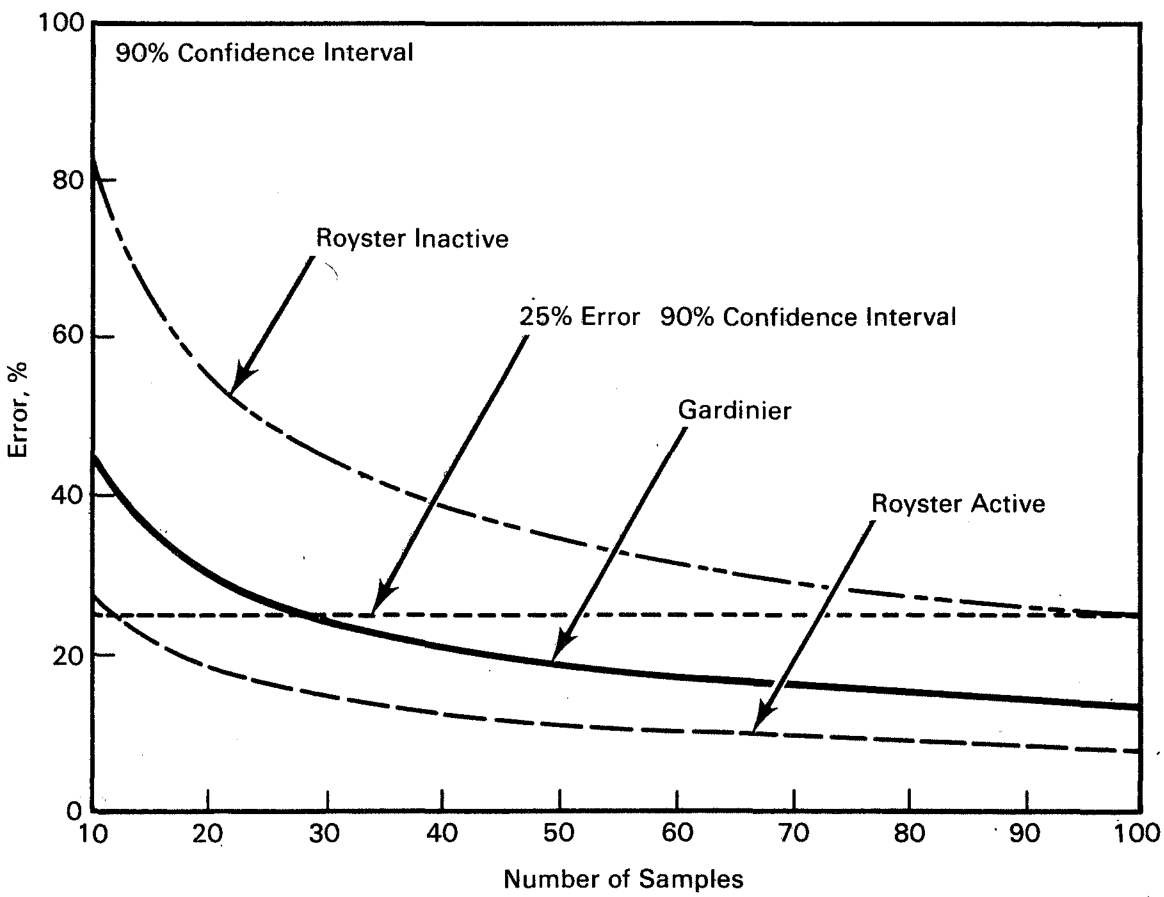


FIGURE 3. Error in Estimated Radon Flux Average for Gardinier and Royster Piles

GARDINIER RADON FLUX MEASUREMENTS

The radon flux from the Gardinier phosphogypsum pile near Tampa, Florida, was measured at 211 locations over a 4-day period from April 30 through May 3, 1985. The sampling interval was ~24 hours. The sampling locations are shown in Figure 4. Most were on drier areas of gypsum on or near the outside construction road. A few locations in the northwest corner of the pile were on wet areas. Since the pile is currently being used and has water ponded in the central areas of the pile, only the outer areas of the pile and a few interior dikes were readily accessible for radon flux measurements. Typical flux measurement locations are shown in Figure 5.

The results of the flux measurements are summarized in Table 1 and presented in detail in Appendix B. The average radon flux over the 4-day measurement period was 19.4 +/-14.9 pCi $m^{-2}s^{-1}$. The average radon flux from the drier areas was 19.9 +/-9.2 pCi $m^{-2}s^{-1}$ (199 locations) while the average for wet areas was a factor of 9 less: 2.2 +/-2.4 pCi $m^{-2}s^{-1}$ (11 locations excluding 1 anomalously high measurement).

The drier areas had a moisture content of about 23 to 40 wt% (dry wt) and the wetter areas had a moisture content of up to 65 wt%. In general, the added moisture reduced the flux (2.2 ±2.4 pCi $m^{-2}s^{-1}$). Location 52, however, had the highest measured flux, 111 pCi $m^{-2}s^{-1}$. This anomaly can not be explained directly but may have resulted from a crack beneath the collector or from an area of gypsum with a higher radium content.

Ten locations on the west side of the pile with an 8- to 15-cm-thick soil cover had an average radon flux of 7.0 +/-5.6, the apparent flux reductions based on cover and uncovered gypsum near to each other ranged from 1.38 to 2.68 except for two locations where the flux was greater from the covered area than the adjacent uncovered area. This could have been caused by a higher radium content, lower moisture content, or higher effusion coefficient in the gypsum below the soil cover than in the nearby uncovered material. Figure 6 shows a typical area where covered and uncovered gypsum were measured. Results of these measurements are presented in Table 2.

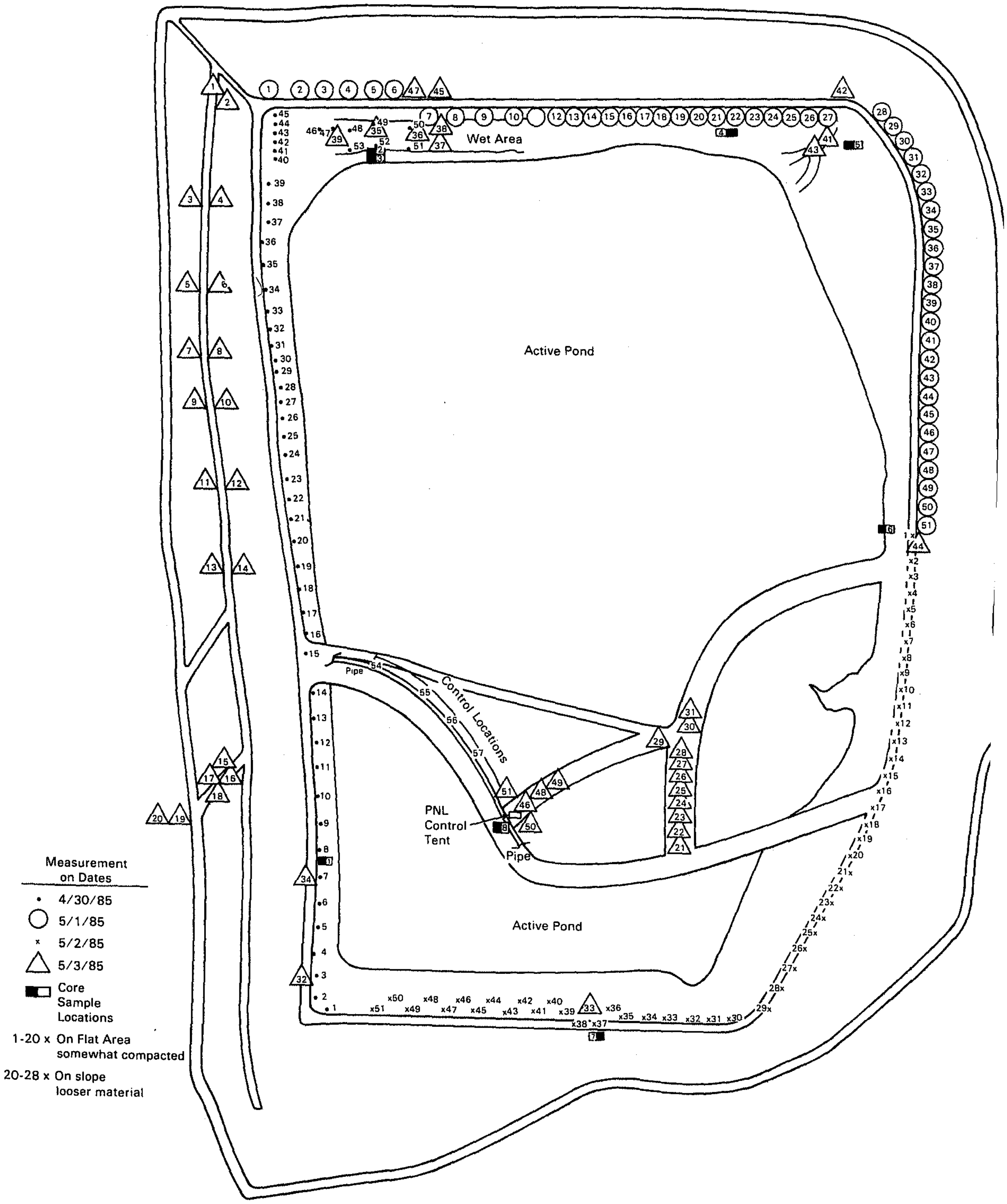
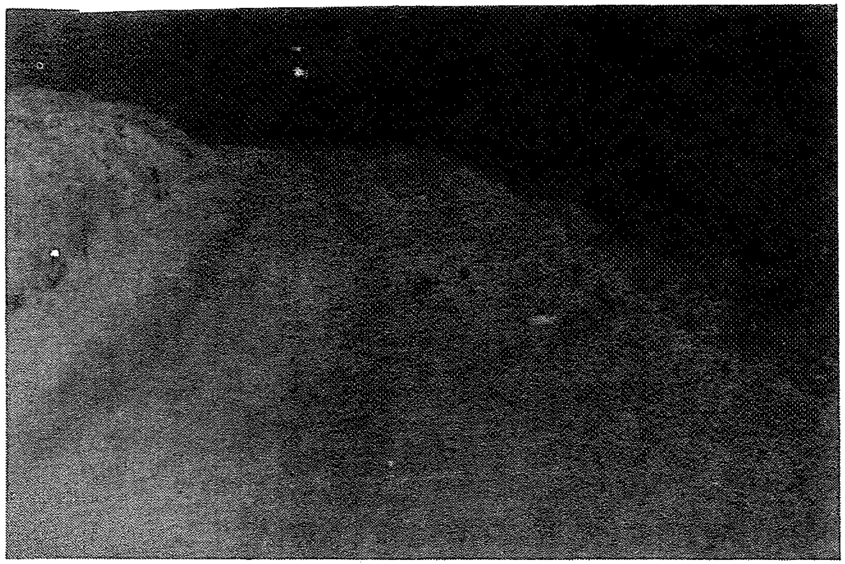
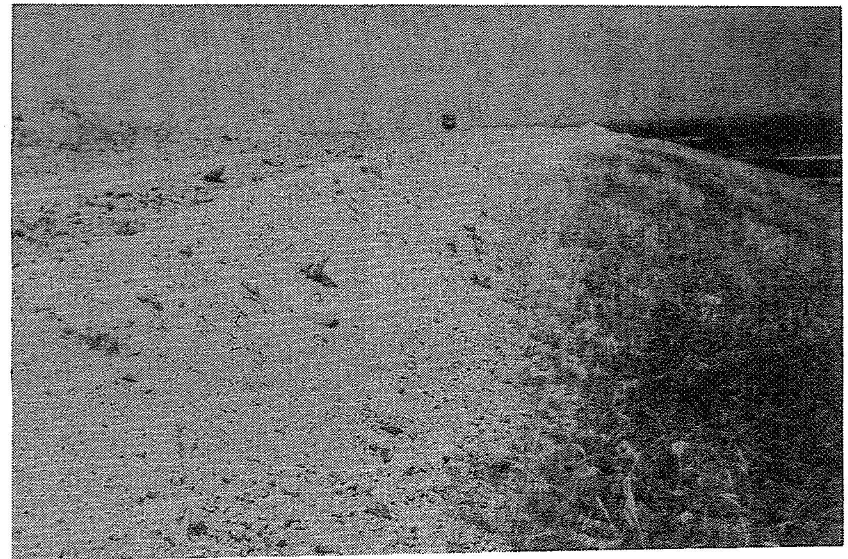


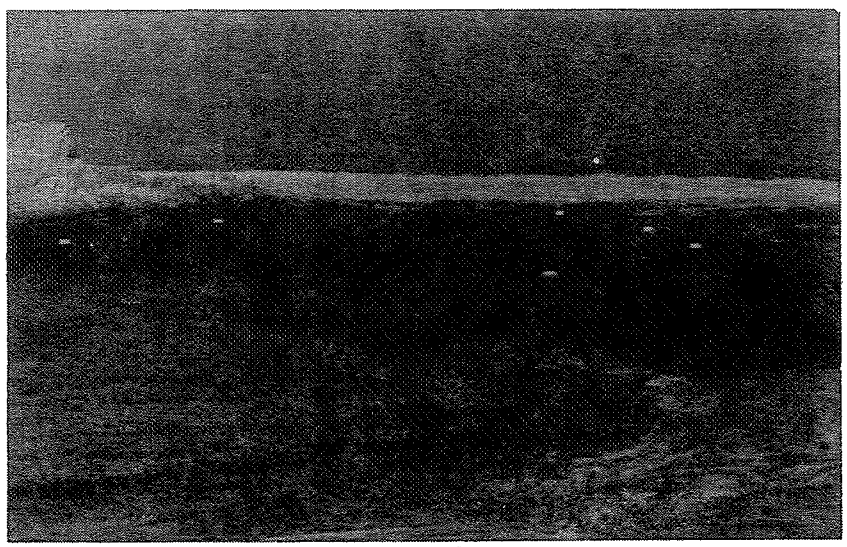
FIGURE 4. Radon Flux Measurement Locations on Gardinier Phosphogypsum P



Next To Road



On Loose Slope



On Wet Area

FIGURE 5. Typical Radon Flux Measurement Locations

TABLE 1. Radon Flux from Gardinier Phosphogypsum Pile, pCi $m^{-2}s^{-1}$

	4/30	5/1	5/2	5/3	Average ±SD
Daily average of all locations	29.4 ±21.8	18.6 ±7.9	17.4 ±8.3	11.5 ±11.7	19.4 ±15.3
Daily average of dry areas	33.2 ±16.6	18.7 ±8.0	16.8 ±7.9	11.4 ±8.9	19.9 ±9.2
Daily average of wet areas	14.9 ±38.8 (1.2 ±1.07)[a]			4.1 ±5.1	10.3 ±28.1 (2.2 ±2.4)[a]

(a) Average does not include location 52, which had a anomalous flux of 111 pCi $m^{-2}s^{-1}$.

TABLE 2. Radon Flux Reduction by Soil Cover, pCi $m^{-2}s^{-1}$

May 3 Location		Relative Flux		
On Road	On Soil	On Road (R)	On Soil Cover (C)	Reduction (R/C)
1	2	24.1	17.5	1.38
3	4	16.8	11.8	1.42
5	6	7.53	4.59	1.64
7	8	6.40	11.7	0.55
9	10	5.41	4.12	1.31
11	12	5.53	6.96	0.79
13	14	8.36	5.42	1.54
15	16	0.19	0.60	0.32
17	18	1.41	0.65	2.17
19	20	12.0	4.47	2.68

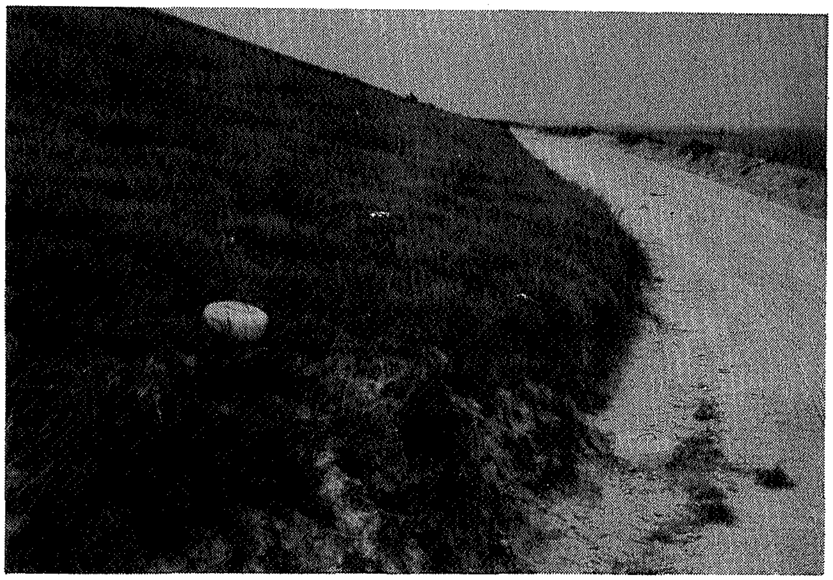


FIGURE 6. Radon Flux Measurement Made on Soil Cover

CONTROL MEASUREMENTS

In addition to the regular sequence of measurements selected locations on a dry area were measured daily. The results of these control measurements are summarized in Table 3. The average radon flux over the 4-day period varied from 32 ±26.7 pCi $m^{-2}s^{-1}$ for location 56 to 11.3 ±4.2 pCi $m^{-2}s^{-1}$ for location 54. The phosphogypsum at control tent location (Figure 7) had an average flux

TABLE 3. Radon Flux from Control Locations on Gardinier Phosphogypsum Pile, pCi $m^{-2}s^{-1}$

Location	4/30	5/1	5/2	5/3	Average ±SD
54	6.6	12.8	14.6	NM	11.3 ±4.2
55	16.9	16.0	11.6	11.6	14.0 ±2.8
56	8.9	12.0	41.7	65.3	32.0 ±26.7
57	30.3	25.3	22.7	20.8	24.8 ±4.1
58	24.7	30.0	26.3	30.9	28.0 ±3.0
CT	11.1	11.2	22.6	21.8	16.7 ±6.4
Average ±SD	16.4 ±9.4	17.9 ±7.9	21.6 ±12.8	28.1 ±23.4	

TABLE 4. Radon Flux from Thin Source, pCi $m^{-2}s^{-1}$

Measured Flux						Calculated Flux[a]
Location	4/30	5/1	5/2	5/3	Average ±SD	
T1	1.83	1.83			1.83 ±0.0	
T2	2.14	1.69			1.92 ±0.32	
T3	2.19	1.73			1.96 ±0.33	
T4	1.97				1.97	
T5	2.2	2.01			2.11 ±0.13	
T6	3.08				3.08	
T7	2.64				2.68	
T8	2.51				2.51	
52		2.45	1.89		2.17 ±0.40	--
53		2.29	2.26		2.28 ±0.02	2.94
59		2.00	2.14		2.17 ±0.10	--
60		2.18	1.90		2.04 ±0.20	2.84
61		2.09	1.98		2.04 ±0.08	2.81
Small Tent		2.0	2.2	3.2	2.47 ±0.64	2.63

(a) Based on R, E, ρ values in Appendix C.

of 16.7 ±6.4 pCi $m^{-2}s^{-1}$. The PNL-developed flow-through radon flux measurement system (Freeman 1981) was used in conjunction with the large-area passive radon collectors.

The large-area passive radon collectors were used to measure the radon flux from a thin layer of mixed phosphogypsum (Figure 8). Since the source is very thin (~ 13 cm), it can be assumed that all of the radon escaping the phosphogypsum particles will diffuse to the surface of the phosphogypsum. Therefore, only the radium content, emanating power, bulk density, and depth of the

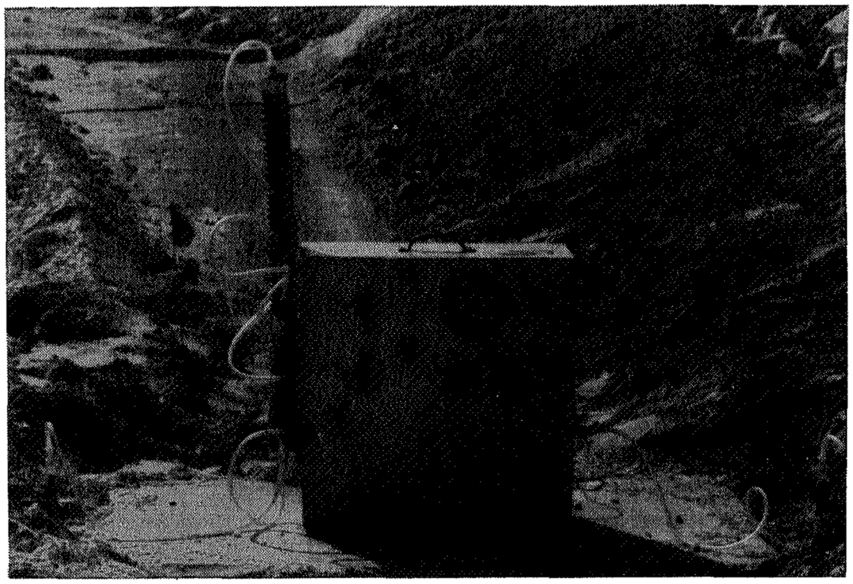


FIGURE 7. PNL Flow-Through System for Radon Flux Control Measurement

gypsum are required to calculate the theoretical flux. This calculated flux can then be compared to the measured flux to compare and calibrate the radon collectors.

The radon flux at the surface of a phosphogypsum pile can be calculated using a one-dimensional, steady-state, radon diffusion equation (Freeman and Hartley 1984) and the physical and radiological properties of the phosphogypsum.

$$\text{Radon flux, } J = RE\rho\sqrt{\lambda D}\ \tanh\left(\sqrt{\lambda/D}\cdot T\right) \quad (3)$$

where R = radium-226 concentration in the phosphogypsum, pCi/g

E = emanating power of phosphogypsum

ρ = bulk density of phosphogypsum

λ = radon decay constant, $2.1 \times 10^{-6} s^{-1}$

D = diffusion coefficient = effective bulk radon diffusion coefficient/porosity, De/p, cm^2/s

T = thickness of phosphogypsum pile, cm.

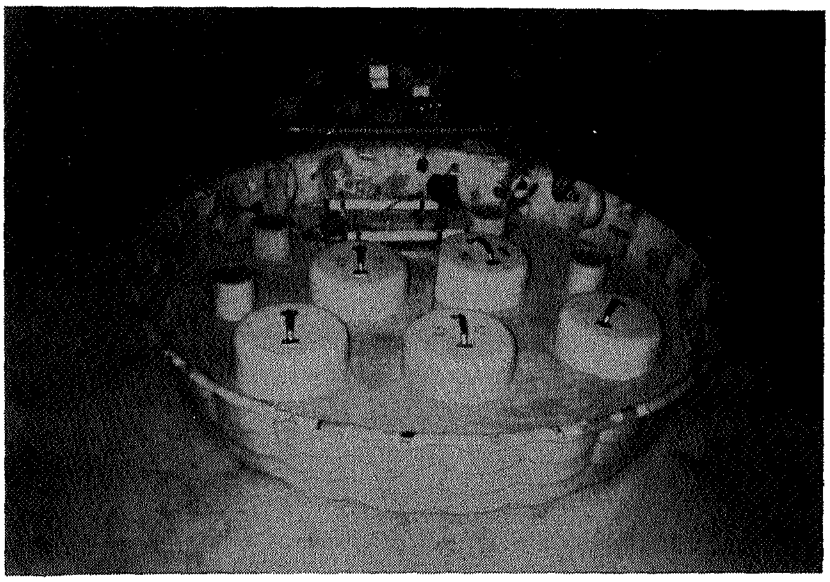


FIGURE 8. Radon Flux Measurements on Thin Source

For a thin source, Equation (3) reduces to

$$J = RE\rho\lambda T \tag{4}$$

Using Equation 4 and the data in Appendix C, the radon flux was calculated for the thin source and compared to the measured values. Only three locations were measured. The measured radon flux was 27% less than the calculated flux. This discrepancy could be caused by not really having a thin source. But since the radon diffusion coefficient for phosphogypsum samples was not known or determined it is difficult to estimate what effect this would have on the calculated value. It is therefore suggested that additional measurements be made on an even thinner, well mixed layer of phosphogypsum to verify this difference.

ROYSTER RADON FLUX MEASUREMENTS

The Royster phosphogypsum pile near Mulberry, Florida, had both active and inactive areas as shown in Figure 9, which also shows the location of the flux measurements. The first sequence of measurements was made on the inactive area of the pile to determine the spacial distribution of radon flux and the cyclic changes over the 4 days of measurements on the inactive area of the pile. Results of these measurements are presented in Table 5. The last set of measurements were made on the active area to determine the average radon release from this area. The results of these measurements are also presented in Table 5. The moisture content of the top 10 cm of the phosphogypsum in the inactive area averaged 14.35 ±5.79 wt% (dry wt) (22 locations) and ranged from 5.44 wt% on the construction road to 25.5 wt% on a very wet area of the pile.

To determine the spacial distribution on an inactive pile, the measurement locations were gridded to ~60-ft centers (see Figure 10). The results of the flux measurements on this grid are summarized in Table 6. The moisture content of the top 10 cm of phosphogypsum in the grid area ranged from 10.5 to 20.2 wt% (dry wt) with an average of 15.13 ±3.50 wt%. The surface of the phosphogypsum was crusted with an wet area ~2.5 cm below the surface.

CONTROL MEASUREMENTS

Selected locations on the inactive area of the pile were measured daily over the 4-day period (Figure 11). The results of these measurements are presented in Table 7.

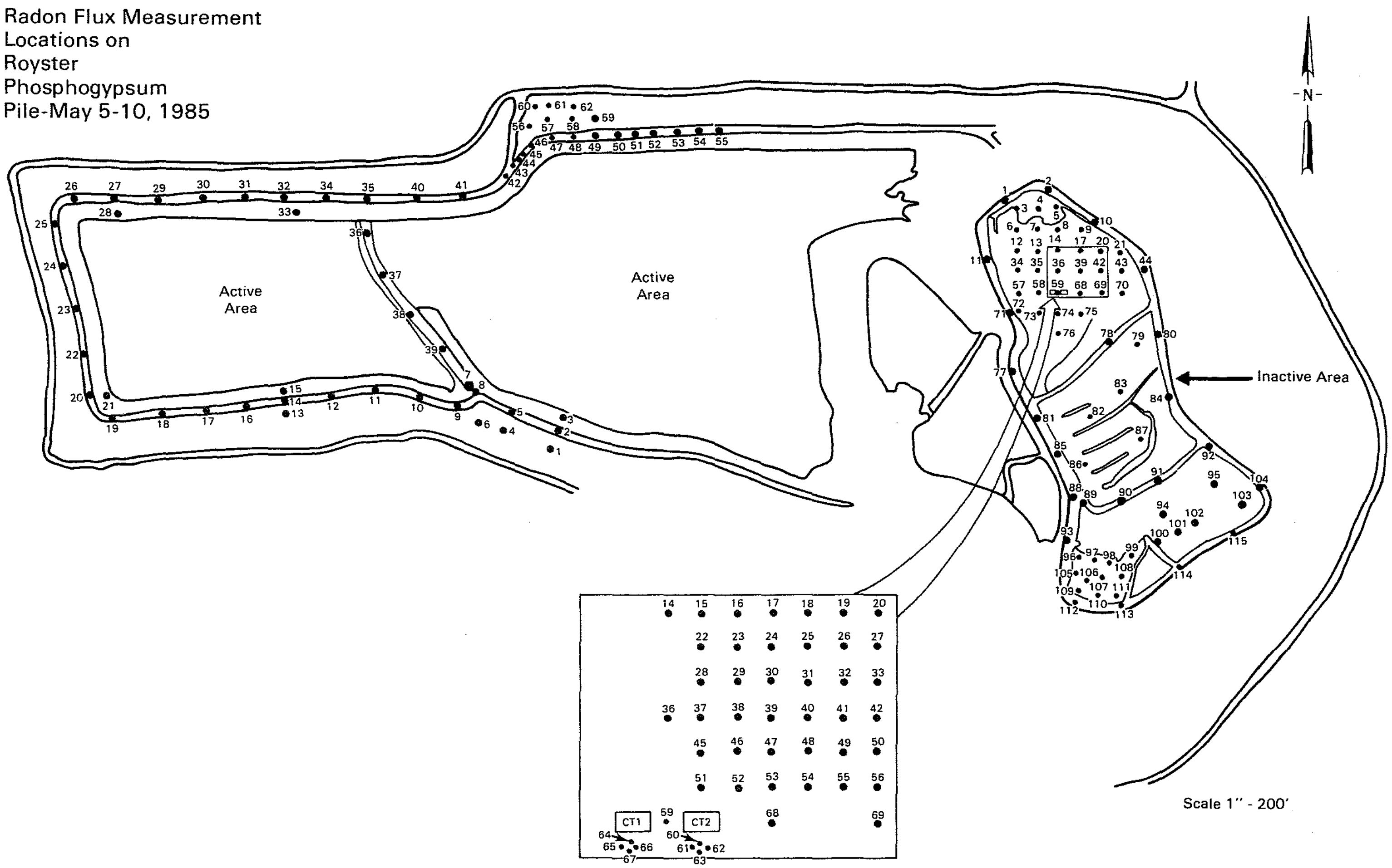


FIGURE 9. Radon Flux Measurement Locations on Royster Phosphogypsum Pile

TABLE 5. Radon Flux from Royster Phosphogypsum Pile, pCi $m^{-2}s^{-1}$

	5/4	5/6	5/7	5/8	5/9	Average
Inactive area	4.7 ±7.7	4.9 ±7.7	5.2 ±4.6	2.9 ±4.4	NM	4.5 ±5.8
Active area					16.7 ±7.8	

TABLE 6. Radon Flux from Grid Area on Royster Inactive Area, pCi $m^{-2}s^{-1}$.

Location	May 6	May 7	May 8	Average ±SD
3	1.05	3.66	3.42	2.71 ±1.44
4	1.14	4.91		3.02 ±2.67
5	4.85	8.54		6.70 ±2.61
6	0.21	0.665		0.44 ±0.32
7	1.05	2.25		1.65 ±0.85
8	0.435	1.85		1.14 ±1.00
9	3.89	3.03		3.46 ±0.61
12	1.80	2.18		1.99 ±0.27
13	4.53	6.44		5.49 ±1.35
14	2.50	2.73		2.62 ±0.16
17	3.68	2.30	3.39	3.12 ±0.73
20	3.22	2.24	4.61	3.36 ±1.19
21	-	6.14		6.14
34	-	1.40		1.40
35	0.345	1.78		1.06 ±1.01
36	2.76	4.34		3.55 ±1.12
39	4.11	2.95	3.53	3.53 ±0.58
42	2.76	2.15	2.35	2.42 ±0.31
43	4.33	4.88		4.61 ±0.39
51	1.01	0.838		0.92 ±0.12
58	1.73	4.29		3.01 ±1.81
59	1.71	2.96	3.38	2.68 ±0.87
68	4.09	2.58		3.34 ±1.07
69	2.89	3.70		3.30 ±0.57
70	10.5	4.14		7.32 ±4.50
72	5.03	2.75		3.89 ±1.61
73	3.53	4.30		3.92 ±0.54
74	2.36	1.34		1.85 ±0.72
75	49.8	34.4		42.1 ±10.9
76	2.60	3.69	3.57	3.29 ±0.60
	4.51 ±9.10	4.31 ±5.94	3.46 ±0.66	

Overall average for large grid: 4.47 ±7.19 pCi $m^{-2}s^{-1}$.

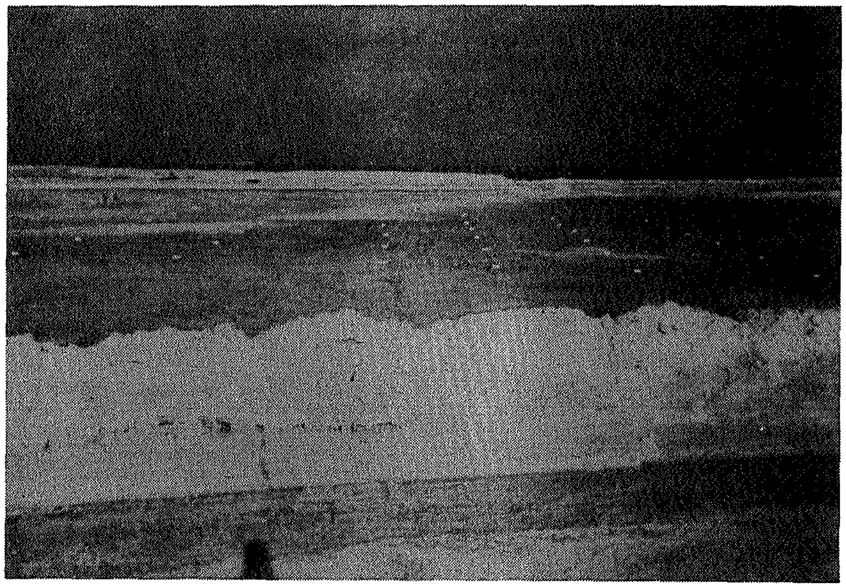


FIGURE 10. Grid Locations on Royster Phosphogypsum Pile

TABLE 7. Radon Flux from Control Areas on Royster Inactive Area, pCi $m^{-2}s^{-1}$

	Location	5/4	5/6	5/7	5/8[a]	Average ±SD
	CT 1[b]		2.86	1.48	NA	2.17 ±0.98
	CT 2[b]		0.50	2.01	NA	1.26 ±1.07
	59	1.71	2.96	3.38	NA	3.17 ±0.30
Group 1	60		3.08	2.49	NA	2.79 ±0.42
	61		4.22	2.72	NA	3.47 ±1.06
	62		3.97	2.87	NA	3.42 ±0.78
	63		4.67	5.25	NA	4.96 ±0.41
		Avg ±SD Group 1	3.99 ±0.67	3.33 ±1.29		
Group 2	64		4.05	2.99	NA	3.52 ±0.75
	65		3.27	3.12	NA	3.20 ±0.11
	66		3.17	4.86	NA	4.02 ±1.20
	67		3.45	3.20	NA	3.33 ±0.18
		Avg ±SD Group 2	3.49 ±0.39	3.54 ±0.88		

(a) Unrecharged charcoal was inadvertently used in radon collectors, resulting in loss of data.
(b) PNL flow-through radon flux measurement systems were used at these locations.

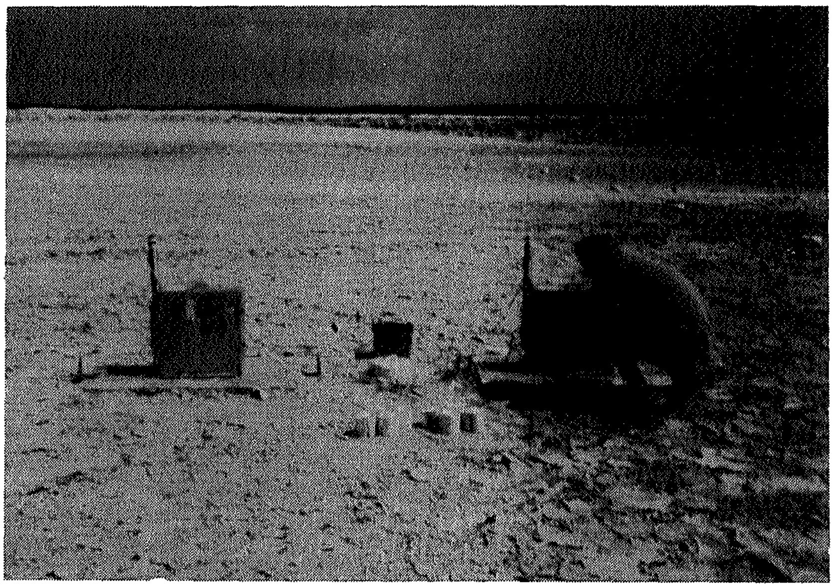


FIGURE 11. Radon Flux Measurements from the Control Locations on an Inactive Area of Royster Phosphogypsum Pile

CONCLUSIONS

wet areas on the Gardinier pile had an average radon flux 9 times r than that of the dry areas.

thin soil cover on Gardinier generally reduced the radon flux, only by a factor of 1.38 to 2.68.

oximately 28 sample locations would be needed for the Gardinier in order to estimate the average radon flux with a 25% error at 90% confidence level. The Royster inactive and active areas d require 93 and 12 sample locations, respectively.

enough data were obtained to quantitatively estimate the cyclic ges that would be expected throughout the year.

RECOMMENDATIONS

- For each new pile, make 30 measurements on accessible portions of the pile. Make a proportionate number of measurements on wet and dry areas (i.e., if 30% of area is wet, make 30 x 0.3 = 9 measurements on the wet areas and 21 measurements on dry areas).
- Use the data from the initial 30 measurements and Equation 2 to estimate the number of locations required for estimating the annual average radon flux from a particular pile.
- Make weekly flux measurements on the same locations and periodically evaluate data from these measurements to adjust the number of measurements that need to be made with time.

REFERENCES

Countess, R. J. 1976. "Radon Flux Measurement with a Charcoal Cannister." Health Physics 31: 455.

Freeman, H. D., and J. N. Hartley. 1984. "Predicting Radon Flux from Uranium Mill Tailings." In Proceedings of Sixth Symposium on Management of Uranium Mill Tailings, Low-Level Waste and Hazardous Waste. Colorado State University, Fort Collins, Colorado.

Freeman, H. D. 1981. "An Improved Radon Flux Measurement System for Uranium Mill Tailings Pile Measurement." In Proceedings of Radiation Hazards in Mining: Control, Measurement and Medical Aspects. Golden, Colorado.

Hartley, J. N., G. W. Gee, E. G. Baker, and H. D. Freeman 1983. 1981 Radon Barrier Field Test at Grand Junction Uranium Mill Tailings Pile. EOW/UMP-0213, PNL-4539, Pacific Northwest Laboratory, Richland, Washington.

Holloway, C. F., et al. 1981. Monitoring for Compliance With Decommissioning Termination Survey Criteria. NUREG/CR-2082, prepared for the U.S. Nuclear Regulatory Commission by Oak Ridge National Laboratory, Oak Ridge, Tennessee.

APPENDIX A

PROCEDURE FOR MAKING RADON FLUX MEASUREMENTS USING LARGE-AREA ACTIVATED CHARCOAL CANISTER (LAACC)

APPENDIX A

PROCEDURE FOR MAKING RADON FLUX MEASUREMENTS USING LARGE-AREA ACTIVATED CHARCOAL CANISTER (LAACC)

INTRODUCTION

Each LAACC is constructed from a PVC end cap, fiberglass screen, and plastic grid and scrubber pads as shown in Figure A.1. The LAACC represents an improvement over the previous standard M1 charcoal canister in that it measures a much larger area. The radon collection mechanism, however, is the same; namely, sorption on activated charcoal. The amount of radon sorbed on the activated charcoal is quantified by gamma-ray spectroscopy of the charcoal using a NaI(Tl) crystal or germanium diode and multichannel analyser. Usually, the ^{214}Bi 609-keV peak is used to determine the radon activity, but many other ^{214}Bi and ^{214}Pb peaks could also be used. The radon flux is calculated from the radon activity using the area of the collector, time of measurement, and radon decay corrections.

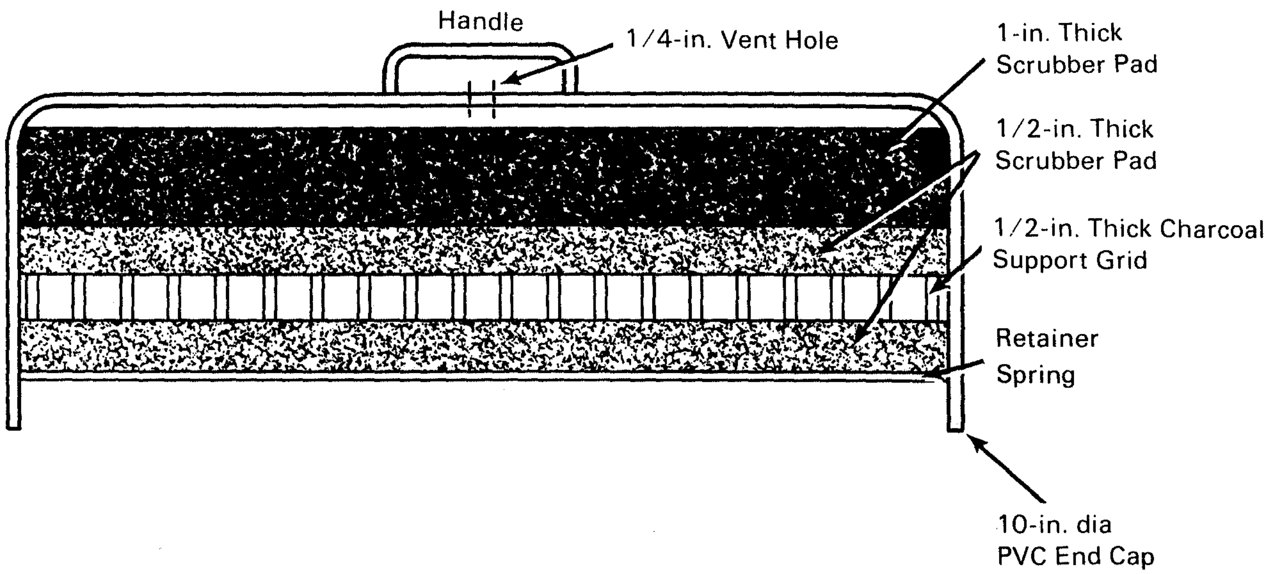


FIGURE A.1. Large-Area Radon Collector

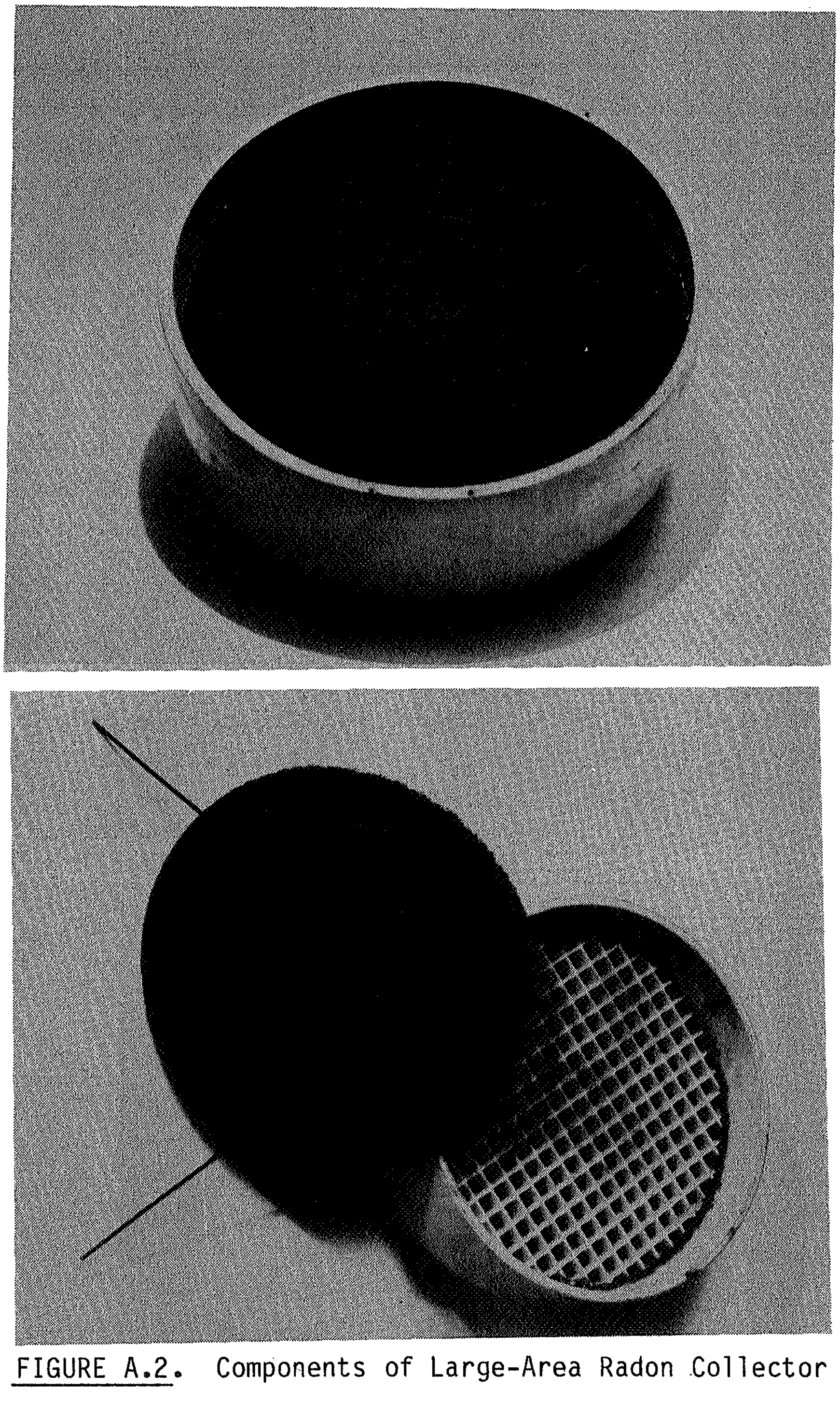


FIGURE A.2. Components of Large-Area Radon Collector

This appendix describes the proper techniques for making the radon flux measurements, including precautions on the proper times to make measurements and on handling of the charcoal before and after making the measurement.

LAACC DESCRIPTION

Figure A.2 shows an exploded view of the components of a LAACC. The LAACC constructed by PNL for the EPA consists of a 10-in. inside diameter (ID) PVC end cap with a 1/4-in. hole drilled in the center and a 5-1/4-in. handle, 1-1/2-in.-thick spacer pads, fiberglass screen, 1/2-in. plastic grid material, and a removable 1/2-in. scrub pad with fiberglass screen attached. The bottom pad and screen are held in the end cap by a piece of 3/32-in.-dia spring steel.

The 1/4-in. hole in the top of the end cap allows atmospheric pressure changes to be transmitted under the end cap and prevents pressure differentials between the inside and outside of the LAACC. Pressure differentials can have detrimental effects on measuring the radon flux by causing advective transport of the radon from the soil.

Activated Charcoal Preparation

The activated charcoal to be used for flux measurements should be thoroughly purged of any radon sorbed from atmospheric sources before being used the first time. This can be accomplished by heating the charcoal in an oven at 110°C for 24 hours. An oven with a circulating fan is preferable. The activated charcoal should then be cooled to room temperature in a place that is as free of radon as possible. Avoid storing the charcoal on or near obvious sources of radon (e.g., at the phosphate mill). After the charcoal is activated in the oven, it should be stored in airtight containers such as taped plastic bags or buckets with sealable lids.

Loading the LAACC

1. Turn the LAACC over on its handle and remove the retainer wire and bottom pad.

2. Pour ~400 mL (EPA "cottage-cheese carton" full) of activated charcoal in the center of the plastic grid. Distribute the charcoal evenly over the grid with your fingers or with a straight-edge.

3. Place pad, screen side toward the charcoal, on the grid.

4. Secure the pad in the LAACC by inserting the retainer wire in the notches on the inside of the LAACC.

5. If several hours will elapse between time of loading and time of deployment of the collectors, then the LAACCs should be placed in plastic bags and sealed with tape.

Making Radon Flux Measurements

1. Make sure the measurement location is fairly level and free from large rocks and vegetation.

2. Place the LAACC on the desired location by firmly rotating the edge of the end cap into the soil. Be careful not to push the lip of the end cap too far into the soil. There should be 1/4 to 1/2 in. of space between the surface being measured and the pad. If the surface to be measured is very hard, seal the edge of the LAACC using loose gypsum or soil.

3. Record the location, LAACC number, date, and time of deployment in a permanent logbook using ink. Do not use loose sheets of paper as they have a tendency to become lost.

4. Allow the LAACC to collect radon for ~24 hours.

5. Remove the LAACC from its measurement location and place in a plastic bag or unsealed in the vehicle if the unloading process is to take place within about an hour. Record the off date and time in the log book using ink.

6. Make gummed labels for each measurement that includes the location, LAACC number, and measurement start and stop dates and times.

7. Transport the LAACCs to a low-radon area for unloading. It is important to unload the LAACCs as soon as possible, especially in warm weather. Otherwise, the radon will begin to desorb from the charcoal to the atmosphere.

Unloading the LAACCs

The charcoal in the LAACCs must be transferred to a container before the quantity of radon on the charcoal can be analysed. The transfer process is described below.

1. Lay the LAACC upside down (on its handle) and remove the retainer wire. Save the wire for reuse.

2. Carefully remove the pad from the LAACC, making sure that any charcoal that clings to the screen is brushed back into the end cap or the funnel.

3. Dump the charcoal in the LAACC into a large bowl or pan. Then transfer the charcoal through a funnel into a "cottage-cheese carton" or other container. Use care to minimize charcoal loss. Place the lid on the "cottage-cheese carton" and seal with vinyl tape.

4. Place the appropriate gummed label on the lid of the "cottage-cheese carton" for identification.

5. Allow 4 hours for equilibration of radon and its daughters before counting.

Counting the Activated Charcoal

The system used to quantify the amount of radon adsorbed on the charcoal consists of a scintillation crystal (NaI) with high-voltage supply, amplifier, and scaler. A multichannel analyser, which would allow the counting system operator to see the peaks of interest and make necessary adjustments if the electronics are not stable, would also be very helpful. The ^{214}Bi 609-keV peak is recommended for use in quantifying the radon. The specifics of operating the counting equipment will be provided by EPA personnel.

To ensure high-quality radon flux data, certain quality assurance procedures must be followed. First, a standard, traceable to the National Bureau of Standards (NBS), must be counted on a daily basis to detect changes in counting system performance. The standard should be made of an NBS radium chloride solution sorbed onto activated charcoal in the same geometry that will be used for radon flux samples. The EPA will provide the standards for counting.

Secondly, a blank should be made of each batch of activated charcoal that is used. If the same batch of charcoal is used on different days, a new blank should be prepared for each day. If time is available, the blanks should be counted over a longer time period than the normal radon flux samples. This longer count time will improve the counting statistics for this low-level sample.

Thirdly, a randomly selected group of samples of 5% to 10% of the total should be recounted to check for leaking containers and reproducibility of counting technique. All counting data should be entered into a permanent notebook using ink.

<u>Radon Flux Calculations</u>

The radon flux is calculated from the net counts, collector area, exposure interval, detector efficiency, and relative counting times. The equation for calculating the flux is:

$$J = \frac{c\lambda^{2}}{K\,A\,E\left(1-e^{-\lambda t_1}\right)\left(e^{-\lambda(t_2-t_1)}-e^{-\lambda(t_3-t_1)}\right)}$$

where J = radon flux, pCi $m^{-2}s^{-1}$

C = net counts under ^{214}Bi 609-keV peak

λ = radon decay constant, 2.097 E-6/s

A = area of collector, m^2

E = efficiency of detector, c/d

K = conversion from d/s to pCi, 0.037 d/s/pCi

t_1 = exposure time, s

t_2 = time from start of measurement to start of counting, s

t_3 = time from start of measurement to end of counting, s.

The radon flux calculations can be greatly simplified by using a computer or programmable calculator. A program for the Hewlett Packard (HP) 41C programmable calculator is given in Table A.1.

TABLE A.1. Hewlett Packard (HP) 41C Program for Calculating Radon Flux[a]

```
01♦LBL "TIME2"
02 "INPUT SAMPLE NO"
03 AON
04 PROMPT
05 PRA
06 ADV
07 AOFF
08 "INPUT DAY1"
09 PROMPT
10 STO 01
11 "INPUT TIME1"
12 PROMPT
13 HR
14 STO 02
15 "INPUT DAY2"
16 PROMPT
17 STO 03
18 "INPUT TIME2"
19 PROMPT
20 HR
21 STO 04
22 ENTER↑
23 RCL 02
24 X>Y?
25 GTO 02
26 RCL 04
27 ENTER↑
28 RCL 02
29 -
30 3600
31 *
32 STO 05
33 RCL 03
34 ENTER↑
35 RCL 01
36 -
37 STO 06
38 86400
39 *
40 RCL 05
41 +
42 STO 06
43 GTO 04
44♦LBL 02
45 24
46 ENTER↑
47 RCL 02
48 -
49 RCL 04
50 +
51 3600
52 *
53 STO 08
54 RCL 03
55 ENTER↑
56 RCL 01
57 -
58 1
59 -
60 86400
61 *
62 RCL 08
63 +
64 STO 06
65♦LBL 04
66 "INPUT T1"
67 FIX 0
68 4
69 PROMPT
70 STO 11
71 INT
72 3600
73 *
74 STO 05
75 RCL 11
76 FRC
77 6000
78 *
79 ST+ 05
80 "T1= "
81 ARCL 05
82 PRA
83 "T2= "
84 ARCL 06
85 PRA
86 RCL 06
87 ENTER↑
88 600
89 +
90 STO 07
91 "T3= "
92 ARCL 07
93 PRA
94 XEQ "RADON"
95 END
```

```
01♦LBL "RADON"
02 2.097 E-6
03 STO 01
04 "INPUT COUNTS"
05 PROMPT
06 STO 04
07 RCL 01
08 X↑2
09 ENTER↑
10 RCL 04
11 *
12 STO 08
13 RCL 02
14 ENTER↑
15 .037
16 *
17 RCL 03
18 *
19 STO 09
20 RCL 05
21 ENTER↑
22 RCL 01
23 *
24 CHS
25 E↑X
26 1
27 -
28 CHS
29 RCL 09
30 *
31 STO 10
32 RCL 06
33 ENTER↑
34 RCL 05
35 -
36 RCL 01
37 *
38 CHS
39 E↑X
40 STO 11
41 RCL 07
42 ENTER↑
43 RCL 05
44 -
45 RCL 01
46 *
47 CHS
48 E↑X
49 RCL 11
50 -
51 CHS
52 STO 12
53 RCL 10
54 *
55 1/X
56 RCL 08
57 *
58 STO 13
59 ST+ 14
60 FIX 0
61 "NET COUNTS="
62 ARCL 04
63 PRA
64 FIX 1
65 "R FLUX= "
66 ARCL 13
67 "├ PCI/M2-S"
68 PRA
69 ADV
70 .END.
```

(a) The following information is provided for using the program:

- store collector area in register 02
- store detector efficiency in register 03
- execute time 2 program
- radon program is used as a subroutine
- day 1 is day measurement was started
- time 1 is time measurement was started (HH.MM)
- day 2 is day charcoal sample was counted
- time 2 is time charcoal sample was counted (HH.MM)
- T1 is exposure time of measurement (HH.MM)
- counts is net counts for ^{214}Bi 609-keV peak.

APPENDIX B

RADON FLUX DATA FROM GARDINIER AND ROYSTER PHOSPHOGYPSUM PILES

APPENDIX B

RADON FLUX FROM GARDINIER AND ROYSTER PHOSPHOGYPSUM PILES

TABLE B.1. Radon Flux Measurements on Gardinier Phosphogypsum Pile

	COLLECTOR ID	DATE ON	TIME ON	FLUX pCi/m2-s
PILE:	1	APR 30	8.30	19.0
	2	APR 30	8.30	25.3
	3	APR 30	8.30	7.87
	4	APR 30	8.30	27.9
	5	APR 30	8.35	37.5
	6	APR 30	8.35	55.6
	7	APR 30	8.35	63.5
	8	APR 30	8.35	47.6
	9	APR 30	8.43	47.8
	10	APR 30	8.43	20.6
	11	APR 30	8.43	24.5
	12	APR 30	8.43	29.9
	13	APR 30	8.43	51.0
	14	APR 30	8.43	41.1
	15	APR 30	8.52	23.3
	16	APR 30	8.52	65.3
	17	APR 30	8.52	38.7
	18	APR 30	8.52	67.8
	19	APR 30	8.52	50.9
	20	APR 30	8.52	23.6
	21	APR 30	8.52	46.2
	22	APR 30	8.52	35.1
	23	APR 30	8.79	50.8
	24	APR 30	8.82	18.7
	25	APR 30	8.82	38.6
	26	APR 30	8.82	19.5
	27	APR 30	8.89	25.4
	28	APR 30	8.83	28.1
	29	APR 30	8.85	8.88
	30	APR 30	8.85	62.4
	31	APR 30	8.93	24.6
	32	APR 30	8.87	26.7
	33	APR 30	8.95	55.1
	34	APR 30	8.89	9.29
	35	APR 30	8.90	50.4
	36	APR 30	8.90	22.3
	37	APR 30	8.92	34.1

TABLE B.1. (contd)

	38	APR 30	8.93	25.2
	39	APR 30	8.93	22.8
	40	APR 30	8.99	23.5
	41	APR 30	9.99	13.1
	42	APR 30	9.00	18.5
	43	APR 30	9.00	39.2
	44	APR 30	9.00	3.33
	45	APR 30	9.02	21.0
	46	APR 30	9.07	2.18
	47	APR 30	9.07	.372
	48	APR 30	9.07	1.84
	49	APR 30	9.09	.224
	50	APR 30	9.09	2.89
	51	APR 30	9.10	.658
	52	APR 30	9.10	111
	53	APR 30	9.12	.339
	54	APR 30	9.30	6.60
	55	APR 30	9.32	16.9
	56	APR 30	9.32	8.92
	57	APR 30	9.32	30.3
	58	APR 30	9.35	24.7
THIN SOURCE:	T1	APR 30	10.33	1.83
	T2	APR 30	10.33	2.14
	T3	APR 30	10.33	2.19
	T4	APR 30	10.33	1.97
	T5	APR 30	10.33	2.20
	T6	APR 30	10.33	3.08
	T7	APR 30	10.33	2.64
	T8	APR 30	10.33	2.51
CONTROL TENT:	CTT	APR 30	10.72	6.64
	CTB	APR 30	10.72	4.56
PILE:	1	MAY 1	8.50	15.7
	2	MAY 1	8.50	9.27
	3	MAY 1	8.52	8.73
	4	MAY 1	8.52	10.4
	5	MAY 1	8.53	8.57
	6	MAY 1	8.70	19.1
	7	MAY 1	8.70	13.0
	8	MAY 1	8.75	9.96
	9	MAY 1	8.75	12.2
	10	MAY 1	8.77	28.8
	11	MAY 1	8.99	21.5
	12	MAY 1	8.99	17.0
	13	MAY 1	9.00	13.5

TABLE B.1 (contd)

14	MAY 1	9.00	6.85
15	MAY 1	9.02	6.31
16	MAY 1	9.02	9.35
17	MAY 1	9.03	29.1
18	MAY 1	9.03	10.7
19	MAY 1	9.05	9.46
20	MAY 1	9.05	9.61
21	MAY 1	9.37	12.3
22	MAY 1	9.37	25.0
23	MAY 1	9.37	11.4
24	MAY 1	9.40	7.92
25	MAY 1	9.40	20.8
26	MAY 1	9.40	21.0
27	MAY 1	9.42	9.99
28	MAY 1	9.42	21.6
29	MAY 1	9.42	21.4
30	MAY 1	9.43	20.3
31	MAY 1	9.67	28.6
32	MAY 1	9.67	28.7
33	MAY 1	9.69	28.6
34	MAY 1	9.69	21.1
35	MAY 1	9.70	36.5
36	MAY 1	9.70	17.6
37	MAY 1	9.72	27.6
38	MAY 1	9.72	35.7
39	MAY 1	9.73	18.4
40	MAY 1	9.73	25.5
41	MAY 1	10.02	19.6
42	MAY 1	10.02	22.7
43	MAY 1	10.03	14.4
44	MAY 1	10.03	16.9
45	MAY 1	10.05	28.5
46	MAY 1	10.05	24.2
47	MAY 1	10.07	18.9
48	MAY 1	10.09	27.3
49	MAY 1	10.12	29.4
50	MAY 1	10.13	NA
51	MAY 1	10.15	23.8
52	MAY 1	14.33	2.45
53	MAY 1	14.33	2.29
54	MAY 1	10.07	12.8
55	MAY 1	10.13	16.0
56	MAY 1	10.13	12.0
57	MAY 1	10.15	25.3
58	MAY 1	10.17	30.0

TABLE B.1. (contd)

	59	MAY 1	14.37	2.00
	60	MAY 1	14.37	2.18
	61	MAY 1	14.37	2.09
THIN SOURCE:	T1	MAY 1	14.33	1.83
	T2	MAY 1	14.33	1.69
	T3	MAY 1	14.33	1.73
	T5	MAY 1	14.33	2.01
CONTROL TENT:	CTT	MAY 1	10.72	4.70
	CTB	MAY 1	10.72	6.50
	SGEL	MAY 1	10.72	.002
PILE:	1	MAY 2	9.23	23.1
	2	MAY 2	9.23	25.3
	3	MAY 2	9.23	18.7
	4	MAY 2	8.97	19.7
	5	MAY 2	8.97	9.92
	6	MAY 2	9.27	22.4
	7	MAY 2	9.27	37.8
	8	MAY 2	9.27	20.7
	9	MAY 2	8.99	23.6
	10	MAY 2	8.99	10.6
	11	MAY 2	9.09	7.91
	12	MAY 2	10.03	10.1
	13	MAY 2	9.45	3.19
	14	MAY 2	10.05	12.7
	15	MAY 2	10.03	5.89
	16	MAY 2	9.02	10.3
	17	MAY 2	9.03	4.11
	18	MAY 2	9.03	10.5
	19	MAY 2	9.03	7.46
	20	MAY 2	9.05	7.42
	21	MAY 2	10.07	43.9
	22	MAY 2	9.52	28.7
	23	MAY 2	10.07	15.5
	24	MAY 2	9.55	17.0
	25	MAY 2	10.09	19.2
	26	MAY 2	9.55	18.2
	27	MAY 2	9.57	19.3
	28	MAY 2	10.10	17.9
	29	MAY 2	10.10	22.7
	30	MAY 2	10.12	17.6
	31	MAY 2	10.12	26.6

TABLE B.1. (contd)

	32	MAY 2	10.13	17.6
	33	MAY 2	10.13	9.81
	34	MAY 2	10.50	22.6
	35	MAY 2	10.33	19.4
	36	MAY 2	10.33	15.8
	37	MAY 2	10.50	19.7
	38	MAY 2	10.35	15.1
	39	MAY 2	10.35	16.1
	40	MAY 2	10.37	12.4
	41	MAY 2	10.39	9.46
	42	MAY 2	10.39	16.6
	43	MAY 2	10.39	24.5
	44	MAY 2	11.10	16.6
	45	MAY 2	10.53	7.94
	46	MAY 2	10.53	18.8
	47	MAY 2	11.12	17.7
	48	MAY 2	10.52	13.4
	49	MAY 2	11.12	21.6
	50	MAY 2	10.53	7.07
	51	MAY 2	10.55	17.5
	52	MAY 2	15.07	1.89
	53	MAY 2	15.07	2.26
	54	MAY 2	11.15	14.6
	55	MAY 2	11.17	11.6
	56	MAY 2	11.19	41.7
	57	MAY 2	11.19	22.7
	58	MAY 2	11.20	26.3
	59	MAY 2	15.07	2.14
	60	MAY 2	15.07	1.90
	61	MAY 2	15.07	1.98
CONTROL TENT:	CTT	MAY 2	11.22	11.5
	CTB	MAY 2	11.22	11.1
	TN1T	MAY 2	11.00	4.77
	TN1B	MAY 2	11.00	5.81
THIN SOURCE:	T1	MAY 2	14.83	NA
	T2	MAY 2	14.83	NA
	T3	MAY 2	14.83	NA
	T5	MAY 2	14.83	NA
PILE:	1	MAY 3	8.85	24.1
	2	MAY 3	8.85	17.5
	3	MAY 3	8.89	16.8

TABLE B.1. (contd)

4	MAY 3	8.89	11.8
5	MAY 3	8.92	7.53
6	MAY 3	8.92	4.59
7	MAY 3	8.95	6.40
8	MAY 3	8.95	11.7
9	MAY 3	8.97	5.41
10	MAY 3	8.97	4.12
11	MAY 3	9.00	5.53
12	MAY 3	9.00	6.96
13	MAY 3	9.03	8.36
14	MAY 3	9.03	5.42
15	MAY 3	9.09	.186
16	MAY 3	9.09	0.60
17	MAY 3	9.13	1.41
18	MAY 3	9.13	.652
19	MAY 3	9.15	12.0
20	MAY 3	9.17	4.47
21	MAY 3	9.59	9.90
22	MAY 3	9.59	44.7
23	MAY 3	9.60	14.5
24	MAY 3	9.60	3.09
25	MAY 3	9.62	14.7
26	MAY 3	9.62	3.13
27	MAY 3	9.63	7.33
28	MAY 3	9.63	14.4
29	MAY 3	9.65	5.07
30	MAY 3	9.65	20.4
31	MAY 3	9.67	9.07
32	MAY 3	9.97	20.3
33	MAY 3	9.99	9.71
34	MAY 3	10.72	16.4
35	MAY 3	10.07	14.6
36	MAY 3	10.09	1.09
37	MAY 3	10.10	6.64
38	MAY 3	10.11	4.79
39	MAY 3	10.07	6.79
40	MAY 3	10.33	12.9
41	MAY 3	10.80	13.0
42	MAY 3	10.37	9.34
43	MAY 3	10.82	8.39
44	MAY 3	10.40	22.2
45	MAY 3	10.87	4.69
46	MAY 3	10.50	2.52
47	MAY 3	10.89	.859
48	MAY 3	10.53	10.2

TABLE B.1. (contd)

	49	MAY 3	10.55	4.23
	50	MAY 3	10.59	.516
	51	MAY 3	10.60	.501
	52	MAY 3	14.22	.912
	53	MAY 3	14.22	1.00
	54	MAY 3	10.73	1.12
	55	MAY 3	10.73	11.6
	56	MAY 3	10.75	65.3
	57	MAY 3	10.75	20.8
	58	MAY 3	10.75	30.9
	59	MAY 3	14.22	.814
	60	MAY 3	14.22	.877
	61	MAY 3	14.22	.527
THIN SOURCE:	T1	MAY 3	14.20	NA
	T2	MAY 3	14.20	9.95
	T3	MAY 3	14.20	11.3
	T5	MAY 3	14.20	12.0
CONTROL TENT:	CTT	MAY 3	10.99	10.7
	CTB	MAY 3	10.99	11.1
	STT	MAY 3	14.33	2.76
	STB	MAY 3	14.33	.0716
	TN1T	MAY 3	11.10	10.7
	TN1B	MAY 3	11.10	5.06

TABLE B.2. Radon Flux Measurements on Royster Phosphogypsum Pile

SAMPLE LOCATIONS	COLLECTOR ID	POND ID	DATE	ON TIME	FLUX pCi/m2-s
3	23	inactive	MAY 4	18.33	1.05
3	23	inactive	MAY 6	8.52	3.66
3	45	inactive	MAY 7	10.87	3.42
4	35	inactive	MAY 4	18.33	1.14
4	37	inactive	MAY 6	8.52	4.91
5	47	inactive	MAY 4	18.33	4.85
5	53	inactive	MAY 6	8.52	8.54
6	32	inactive	MAY 6	8.50	.665
7	54	inactive	MAY 4	18.27	1.05
7	49	inactive	MAY 6	8.50	2.25
7	31	inactive	MAY 7	10.92	1.58
8	37	inactive	MAY 4	18.27	.435
8	14	inactive	MAY 6	8.50	1.85
9	43	inactive	MAY 4	18.27	3.89
9	12	inactive	MAY 6	8.50	3.03
10	11	inactive	MAY 4	19.09	12.1
10	26	inactive	MAY 6	8.69	16.1
10	18	inactive	MAY 7	10.57	14.6
12	27	inactive	MAY 4	18.23	1.80
12	47	inactive	MAY 6	8.37	2.18
13	7	inactive	MAY 4	18.23	4.53
13	6	inactive	MAY 6	8.40	6.44
14	58	inactive	MAY 4	18.23	2.50
14	51	inactive	MAY 6	8.37	2.73
15	38	inactive	MAY 7	10.49	4.22
16	6	inactive	MAY 4	18.27	0.21
16	3	inactive	MAY 7	10.43	2.79
17	26	inactive	MAY 4	18.23	3.68
17	43	inactive	MAY 6	8.37	2.30
17	52	inactive	MAY 7	10.43	3.39
18	10	inactive	MAY 7	10.45	2.08
19	32	inactive	MAY 7	10.45	7.00
20	57	inactive	MAY 4	18.23	3.22
20	60	inactive	MAY 6	8.37	2.24
20	42	inactive	MAY 7	10.50	4.61
21	24	inactive	MAY 4	18.27	3.88
21	8	inactive	MAY 6	8.37	6.14
22	41	inactive	MAY 7	10.40	3.87
23	34	inactive	MAY 7	10.45	2.63
24	26	inactive	MAY 7	10.45	4.25
24	44	inactive	MAY 8	9.70	1.29
25	2	inactive	MAY 7	10.45	2.40

TABLE B.2. (contd)

25	38	inactive	MAY 8	9.70	2.17
26	58	inactive	MAY 7	10.45	1.69
27	50	inactive	MAY 7	10.83	4.41
27	30	inactive	MAY 8	9.60	23.3
28	21	inactive	MAY 7	10.40	4.36
28	47	inactive	MAY 8	9.60	3.86
29	44	inactive	MAY 7	10.40	2.45
29	37	inactive	MAY 8	9.62	2.32
30	1	inactive	MAY 7	10.39	4.15
30	56	inactive	MAY 8	9.60	1.96
31	40	inactive	MAY 7	10.39	4.08
31	1	inactive	MAY 8	9.60	6.37
32	60	inactive	MAY 7	10.39	7.84
32	3	inactive	MAY 8	9.60	.355
33	33	inactive	MAY 7	10.39	3.83
33	23	inactive	MAY 8	9.60	1.27
34	8	inactive	MAY 4	18.15	NA
34	39	inactive	MAY 6	8.32	1.40
35	45	inactive	MAY 4	18.15	.345
35	19	inactive	MAY 6	8.32	1.78
36	21	inactive	MAY 4	18.15	2.76
36	36	inactive	MAY 6	8.32	4.34
37	9	inactive	MAY 7	10.32	2.82
37	61	inactive	MAY 8	9.50	.829
38	15	inactive	MAY 7	10.32	7.86
38	15	inactive	MAY 8	9.50	3.34
39	40	inactive	MAY 4	18.15	4.11
39	56	inactive	MAY 6	8.32	2.95
39	13	inactive	MAY 7	10.33	3.53
39	34	inactive	MAY 8	9.50	1.25
40	16	inactive	MAY 7	10.33	2.9
40	9	inactive	MAY 8	9.50	3.22
41	5	inactive	MAY 7	10.37	4.18
41	41	inactive	MAY 8	9.60	2.39
42	39	inactive	MAY 4	18.15	2.76
42	13	inactive	MAY 6	8.32	2.15
42	47	inactive	MAY 7	10.37	2.35
42	43	inactive	MAY 8	9.60	.559
43	14	inactive	MAY 4	18.15	4.33
43	17	inactive	MAY 6	8.32	4.88
44	31	inactive	MAY 4	19.07	7.18
44	2	inactive	MAY 6	8.65	9.93
44	12	inactive	MAY 7	10.59	9.11
45	29	inactive	MAY 7	10.23	3.53
45	49	inactive	MAY 8	9.45	2.91

TABLE B.2. (contd)

46	43	inactive	MAY 7	10.32	2.23
46	33	inactive	MAY 8	9.45	1.08
47	53	inactive	MAY 7	10.27	3.13
47	21	inactive	MAY 8	9.45	2.43
48	8	inactive	MAY 7	10.32	2.59
48	51	inactive	MAY 8	9.45	2.16
49	49	inactive	MAY 7	10.33	3.94
49	28	inactive	MAY 8	9.37	2.21
50	37	inactive	MAY 7	10.33	4.12
50	5	inactive	MAY 8	9.37	.673
51	30	inactive	MAY 7	10.23	2.65
51	29	inactive	MAY 8	9.32	.303
52	23	inactive	MAY 7	10.25	3.53
52	42	inactive	MAY 8	9.32	.276
53	52	inactive	MAY 8	9.32	1.20
54	36	inactive	MAY 7	10.27	13.7
54	32	inactive	MAY 8	9.32	15.1
55	56	inactive	MAY 7	10.27	8.00
55	50	inactive	MAY 8	9.37	3.03
56	51	inactive	MAY 7	10.33	3.75
56	58	inactive	MAY 8	9.37	.371
57	55	inactive	MAY 4	18.13	1.01
57	59	inactive	MAY 6	8.27	.838
57	4	inactive	MAY 7	10.80	1.13
58	25	inactive	MAY 4	18.13	1.73
58	9	inactive	MAY 6	8.27	4.26
59	56	inactive	MAY 4	18.13	1.71
59	33	inactive	MAY 6	8.27	2.96
59	28	inactive	MAY 7	10.97	3.38
60	LL8	inactive	MAY 6	9.69	3.08
60	LL5	inactive	MAY 7	11.13	2.49
61	LL7	inactive	MAY 6	9.69	4.22
61	LL1	inactive	MAY 7	11.13	2.72
62	LL1	inactive	MAY 6	9.69	3.97
62	LL8	inactive	MAY 7	11.13	2.87
63	LL3	inactive	MAY 6	9.69	4.67
63	LL4	inactive	MAY 7	11.13	5.25
64	LL2	inactive	MAY 6	9.69	4.05
64	LL10	inactive	MAY 7	11.13	2.99
65	LL4	inactive	MAY 6	9.69	3.27
65	LL2	inactive	MAY 7	11.13	3.12
66	LL5	inactive	MAY 6	9.69	3.17
66	LL3	inactive	MAY 7	11.13	4.86
67	LL10	inactive	MAY 6	9.69	3.45
67	LL7	inactive	MAY 7	11.13	3.20

TABLE B.2. (contd)

68	34	inactive	MAY 4	18.13	4.09
68	30	inactive	MAY 6	8.27	2.58
69	46	inactive	MAY 4	18.13	2.89
69	52	inactive	MAY 6	8.27	3.70
70	53	inactive	MAY 4	18.13	10.5
70	24	inactive	MAY 6	8.27	4.14
72	12	inactive	MAY 4	18.07	5.03
72	16	inactive	MAY 6	8.22	2.75
73	32	inactive	MAY 4	18.07	3.53
73	15	inactive	MAY 6	8.22	4.30
74	22	inactive	MAY 4	18.07	2.36
74	40	inactive	MAY 6	8.22	1.34
75	10	inactive	MAY 4	18.07	49.8
75	29	inactive	MAY 6	8.22	34.4
76	41	inactive	MAY 4	18.39	2.60
76	1	inactive	MAY 6	8.23	3.69
76	61	inactive	MAY 7	10.79	3.57
80	1	inactive	MAY 4	19.05	4.11
80	18	inactive	MAY 6	8.69	6.45
80	22	inactive	MAY 7	10.60	8.12
84	4	inactive	MAY 4	19.02	8.98
84	3	inactive	MAY 6	8.72	13.3
84	25	inactive	MAY 7	10.62	11.89
86	20	inactive	MAY 4	18.85	1.04
86	25	inactive	MAY 6	8.70	2.20
86	14	inactive	MAY 7	11.32	.738
87	3	inactive	MAY 4	18.85	9.08
87	21	inactive	MAY 6	8.70	6.93
87	24	inactive	MAY 7	11.32	5.79
88	28	inactive	MAY 4	18.80	31.8
88	22	inactive	MAY 6	8.73	29.2
89	2	inactive	MAY 4	18.80	.879
89	38	inactive	MAY 6	8.80	1.91
90	15	inactive	MAY 4	18.80	1.22
90	58	inactive	MAY 6	8.80	3.32
90	7	inactive	MAY 7	11.39	3.97
91	16	inactive	MAY 4	18.80	5.13
91	5	inactive	MAY 6	8.80	11.1
91	46	inactive	MAY 7	11.39	7.53
92	19	inactive	MAY 4	18.97	5.47
92	44	inactive	MAY 6	8.70	8.00
92	48	inactive	MAY 7	10.63	9.09
96	44	inactive	MAY 4	18.52	3.88
96	27	inactive	MAY 6	8.87	2.04
96	35	inactive	MAY 7	10.47	.383

TABLE B.2. (contd)

97	33	inactive	MAY 4	18.52	.105
97	57	inactive	MAY 6	8.87	0.32
97	57	inactive	MAY 7	11.37	29.1
98	30	inactive	MAY 4	18.52	6.15
98	61	inactive	MAY 6	8.87	.548
98	55	inactive	MAY 7	11.47	1.37
99	38	inactive	MAY 4	18.52	.292
99	50	inactive	MAY 6	8.87	5.27
100	17	inactive	MAY 4	18.67	.266
100	4	inactive	MAY 6	9.00	2.59
101	13	inactive	MAY 4	18.67	1.09
101	46	inactive	MAY 6	9.00	1.04
102	7	inactive	MAY 6	9.00	1.62
102	49	inactive	MAY 4	18.77	4.34
102	20	inactive	MAY 7	11.47	4.27
104	61	inactive	MAY 4	19.92	1.59
104	28	inactive	MAY 6	8.87	3.40
104	59	inactive	MAY 7	10.82	5.37
105	51	inactive	MAY 4	18.55	1.38
105	48	inactive	MAY 6	8.93	2.08
106	9	inactive	MAY 4	18.55	.822
106	41	inactive	MAY 6	8.93	2.19
106	6	inactive	MAY 7	11.42	2.03
107	29	inactive	MAY 4	18.55	.328
107	35	inactive	MAY 6	8.93	.539
108	52	inactive	MAY 4	18.55	0
108	10	inactive	MAY 6	8.93	0.48
109	17	inactive	MAY 7	11.47	1.02
109	5	inactive	MAY 4	18.52	1.04
109	20	inactive	MAY 6	8.82	1.96
53	19	inactive	MAY 7	10.25	2.65
110	42	inactive	MAY 4	18.52	1.04
110	42	inactive	MAY 6	9.00	1.97
111	36	inactive	MAY 4	18.52	.122
111	45	inactive	MAY 6	9.00	3.11
112	60	inactive	MAY 4	19.87	10.3
112	34	inactive	MAY 6	8.83	9.05
112	39	inactive	MAY 7	10.75	8.24
113	48	inactive	MAY 4	18.89	4.07
113	55	inactive	MAY 6	8.89	3.72
113	11	inactive	MAY 7	10.77	5.80
114	18	inactive	MAY 4	18.90	7.16
114	31	inactive	MAY 6	8.85	4.42
114	27	inactive	MAY 7	10.79	8.20
115	59	inactive	MAY 4	18.92	17.6

TABLE B.2. (contd)

115	54	inactive	MAY 6	8.87	14.3
115	54	inactive	MAY 7	10.80	18.1
	T1T	inactive	MAY 6	9.29	1.17
	T1B	inactive	MAY 6	9.29	.696
	T2T	inactive	MAY 6	9.29	.489
	T2B	inactive	MAY 6	9.29	.0139
	CT1T	inactive	MAY 7	11.13	.817
	CT1B	inactive	MAY 7	11.13	.609
	CT2T	inactive	MAY 7	11.15	1.19
	CT2B	inactive	MAY 7	11.15	.828
1	11	active	MAY 9	11.45	15.0
2	8	active	MAY 9	11.45	17.3
3	3	active	MAY 9	11.45	1.02
4	56	active	MAY 9	11.43	25.9
5	28	active	MAY 9	11.42	25.9
6	52	active	MAY 9	11.42	28.9
7	19	active	MAY 9	10.63	10.6
8	41	active	MAY 9	10.77	5.77
9	22	active	MAY 9	10.77	23.5
10	55	active	MAY 9	10.79	19.6
11	34	active	MAY 9	10.80	18.8
12	61	active	MAY 9	10.80	16.1
13	43	active	MAY 9	11.39	25.2
14	45	active	MAY 9	10.82	10.2
15	31	active	MAY 9	11.37	4.34
16	46	active	MAY 9	10.83	14.3
17	30	active	MAY 9	10.83	13.2
18	32	active	MAY 9	10.85	4.06
19	57	active	MAY 9	10.87	14.8
20	24	active	MAY 9	10.87	23.8
21	49	active	MAY 9	10.97	4.30
22	16	active	MAY 9	10.99	2.55
23	36	active	MAY 9	11.00	15.6
24	29	active	MAY 9	11.00	18.1
25	44	active	MAY 9	11.02	17.2
26	60	active	MAY 9	11.02	23.8
27	15	active	MAY 9	11.03	23.6
29	33	active	MAY 9	11.05	21.8
30	20	active	MAY 9	11.07	20.6
31	48	active	MAY 9	11.09	24.1
32	26	active	MAY 9	11.09	16.7
33	47	active	MAY 9	11.09	.541

TABLE B.2. (contd)

34	54	active	MAY 9	11.12	20.1
35	59	active	MAY 9	10.95	16.2
36	2	active	MAY 9	10.73	13.1
37	38	active	MAY 9	10.69	25.9
38	51	active	MAY 9	10.65	2.44
39	17	active	MAY 9	10.63	19.0
40	40	active	MAY 9	10.97	23.2
41	58	active	MAY 9	10.99	25.5
42	35	active	MAY 9	11.00	32.3
43	7	active	MAY 9	11.04	27.6
45	21	active	MAY 9	11.03	20.9
46	18	active	MAY 9	11.05	19.9
47	6	active	MAY 9	11.05	14.8
48	5	active	MAY 9	11.07	16.5
49	12	active	MAY 9	11.09	21.5
50	23	active	MAY 9	11.07	21.9
51	37	active	MAY 9	11.39	13.5
52	13	active	MAY 9	11.40	13.8
53	1	active	MAY 9	11.40	8.48
54	10	active	MAY 9	11.42	20.6
55	14	active	MAY 9	11.42	15.7
56	50	active	MAY 9	11.23	11.6
57	25	active	MAY 9	11.25	18.4
58	53	active	MAY 9	11.27	26.3
59	27	active	MAY 9	11.27	24.5
60	4	active	MAY 9	11.23	21.4
61	42	active	MAY 9	11.27	12.5
62	39	active	MAY 9	11.29	3.18

TABLE B.3. QA Counting for Radon Flux Measurements on Gardinier Pile

RADON COLLECTOR NUMBER	ON DATE 1985	ORIGINAL pCi/m2-s	REPEAT pCi/m2-s	% DIFF.
3	APRIL 30	7.87	6.50	17.41
T4	APRIL 30	1.97	1.99	1.02
10	APRIL 30	20.6	20.5	0.49
20	APRIL 30	23.6	24.3	2.97
29	APRIL 30	8.88	7.35	17.23
30	APRIL 30	62.4	63.8	2.24
40	APRIL 30	23.5	23.0	2.13
50	APRIL 30	2.89	2.90	0.35
6	MAY 1	19.1	19.1	0.00
17	MAY 1	29.1	29.3	0.69
24	MAY 1	7.92	8.08	2.02
35	MAY 1	36.5	36.8	0.82
45	MAY 1	28.5	28.8	1.05
58	MAY 1	30.0	30.1	0.33
5	MAY 2	9.92	10.0	0.81
17	MAY 2	4.11	4.05	1.46
21	MAY 2	43.9	43.8	0.23
33	MAY 2	9.81	9.79	0.20
45	MAY 2	7.94	7.90	0.50
56	MAY 2	41.7	41.5	0.48
5	MAY 3	7.53	7.54	0.13
15	MAY 3	.186	.169	9.14
22	MAY 3	44.7	45.8	2.46
31	MAY 3	9.07	9.07	0.00
44	MAY 3	22.2	22.3	0.45
56	MAY 3	65.3	64.0	1.99

TABLE B.4. QA Counting for Radon Flux Measurements on Royster Pile

	RADON COLLECTOR NUMBER	ON DATE	ORIGINAL pCi/m2-s	REPEAT pCi/m2-s	% DIFF
	6	MAY 4	0.210	0.419	99.52
	19	MAY 4	5.470	5.680	3.839
	28	MAY 4	30.80	30.90	0.325
	37	MAY 4	0.435	0.216	50.34
	47	MAY 4	4.850	3.87	20.21
	52	MAY 4	0.000	0.139	
Count Syst #1	6	MAY 4	0.210	0.431	105.2
	37	MAY 4	0.435	0.476	9.425
	52	MAY 4	0.000	0.172	
Count Syst #2	6	MAY 4	0.210	0.372	77.14
	37	MAY 4	0.440	0.412	6.364
	52	MAY 4	0.000	0.146	
	7	MAY 6	1.620	1.640	1.235
	19	MAY 6	1.780	1.740	2.247
	28	MAY 6	3.400	3.270	3.824
	38	MAY 6	1.910	1.930	1.047
	46	MAY 6	1.040	1.020	1.923
	L7	MAY 6	4.220	4.330	2.607
	5	MAY 7	4.180	4.220	0.957
	15	MAY 7	7.860	7.910	0.636
	30	MAY 7	2.650	2.650	0.000
	40	MAY 7	4.080	4.200	2.941
	55	MAY 7	1.370	1.410	2.920
	5	MAY 8	0.673	0.619	8.024
	34	MAY 8	1.250	1.320	5.600
	44	MAY 8	1.290	1.210	6.202
	61	MAY 8	0.829	0.844	1.809
	3	MAY 9	1.020	0.923	9.510
	15	MAY 9	23.60	23.40	0.847
	45	MAY 9	10.20	10.00	1.961
	22	MAY 9	23.50	23.10	1.702
	35	MAY 9	32.30	32.00	0.929
	55	MAY 9	19.60	19.50	0.510

APPENDIX C

PHYSICAL AND RADIOLOGICAL PROPERTIES OF SELECTED PHOSPHOGYPSUM SAMPLES

APPENDIX C

PHYSICAL AND RADIOLOGICAL PROPERTIES OF SELECTED PHOSPHOGYPSUM SAMPLES

Location	Moisture, wt% (dry wt)	Density, g/cc (dry wt)	Emanating Power	^{226}Ra, pCi/g
Tub-53	19.6	0.93	0.340	32.39
Tub-60	19.5	0.97	0.352	33.67
Tub-61	19.8	0.94	0.326	34.02
Small tent	16.8	0.92	0.326	31.82
Gardinier 1	21.7		0.438	38.77
Gardinier 3	33.0		0.277	35.36
Gardinier 5	17.8		0.394	37.06
Gardinier 7	18.9		0.237	33.05
Gardinier ctrl 1	9.4		0.237	27.93
Gardinier near ctrl	11.2		0.243	33.84
Gardinier ctrl 2	11.9		0.221	28.29
Royster center ctrl	15.0		0.250	36.23
Royster ctrl tent 2a	12.3		0.256	29.90
Royster ctrl tent 2b	15.2		0.245	29.70