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SMALL-SCALE FIELD TEST OF SIMPLE EARTHEN
COVERS FOR URANIUM MILL TAILINGS

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ABSTRACT

Field tests of earthen cover materials were conducted on tailings piles at Salt Lake City and Mexican Hat, Utah and at Grand Junction, Colorado. The cover tests were contained in 1.2 m (4 ft) diameter columns buried in the tailings, and involved local soils of 2.4 - 3.7 m (8-12 ft) thickness. The performances of the covers were evaluated with respect to their reduction of the radon fluxes escaping from the bare tailings. A radon diffusion coefficient of $0.036 \text{ cm}^2/\text{s}$ was obtained for the 12 ft cover at Mexican Hat, which reduced the radon flux from 99 to 10 $\text{pCi}/\text{m}^2\text{s}$. At Grand Junction, diffusion coefficients of 0.024 and 0.029 were respectively obtained for 8 and 12 ft covers, which respectively reduced radon fluxes to 250 and 100 $\text{pCi}/\text{m}^2\text{s}$. The higher fluxes resulted from the much higher 2000 $\text{pCi}/\text{m}^2\text{s}$ source flux at this site. At Salt Lake City, the measured diffusion coefficient of $0.00034 \text{ cm}^2/\text{s}$ is believed to result from high moisture in the lower part of the cover. The radon flux from this 12 ft cover was 0.8 $\text{pCi}/\text{m}^2\text{s}$, and was dominated by the radium content of the cover soil. Radon gas concentration profiles measured in the covers were consistent with the measured radon flux data. The tests were conservative in their use of lower soil compactions than would be obtained in a large-scale field application.

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1. INTRODUCTION

A series of field tests has been conducted during the past year to provide benchmark data on the performance of simple, single-layer earthen covers at three uranium tailings sites. The performance of the covers was evaluated in terms of their reduction of radon gas releases, although moisture profiles and other cover parameters were also monitored. The tests were designed to evaluate the effectiveness of local soils applied with minimum engineering design or compaction effort. The tests, therefore, tend to represent a lowest-cost, and perhaps a worst-case scenario for tailings reclamation: i.e., one in which soils are simply spread over a tailings pile and compacted by the haul trucks.

The field benchmark tests are part of a major research program being conducted by the U.S. Department of Energy to develop technology for uranium tailings disposal. Other research under this program has considered highly-engineered cover and liner systems for containing uranium tailings, and biobarriers for preventing plant and animal intrusion. The present tests with simple earthen covers thus provide a comparative basis for evaluating the effectiveness of more highly-engineered systems and their proportionately higher costs. These tests were conducted on the inactive tailings piles at Salt Lake City; Mexican Hat, Utah; and Grand Junction, Colorado. The test covers were installed during the summer of 1981 (Ri81) and have been monitored during the following year. This report describes the experimental details of the cover tests, the data that were collected during the one-year monitoring period, and the conclusions that were drawn from the experiments.

2. EXPERIMENT DESIGN

The field benchmark tests each consisted of large soil columns which were mostly buried in tailings at each of the three sites. The columns were designed to demonstrate the amount of cover soil needed for radon flux attenuation if the soil were placed using minimal preparation and compaction. The effectiveness of the soil cover was determined by comparison of the radon fluxes from the surface of the soil columns with those from the bare tailings just prior to placement of the cover soil. Details of the column construction and soil characteristics are given in the following paragraphs.

2.1 COLUMN CONSTRUCTION

The soil columns for each of the tests were constructed from 122-cm (4 ft) diameter corrugated aluminum conduit which were open at both ends. Two columns of different lengths, 427-cm and 305-cm (14 ft and 10 ft), were constructed at the Salt Lake City and Mexican Hat tailings piles. The Grand Junction columns are illustrated schematically in Figure 2-1. The columns at Salt Lake City and Mexican Hat were similar to the taller column in Figure 2-1.

Prior to placing the aluminum pipes in the ground, moisture and temperature sensors and soil gas sampling ports were installed at regular intervals as illustrated in Figure 2-1. The sensors and ports were located at the center of the aluminum pipe, and the associated wires and tubes extended through seals in the side of the pipe and up to an access point

NOTE: EACH 'X' INDICATES THE LOCATION OF A GAS SAMPLER WITH A MOISTURE / TEMPERATURE PROBE NEARBY

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FIGURE 2-1. SCHEMATIC DIAGRAM OF THE COVER TEST COLUMNS AT THE TAILINGS PILE.

located at the top of the column. At the Mexican Hat site, an additional gas sampling port was located in the tailings outside the column at the same depth as the bottom port shown in Figure 2-1. The extra port was designed to examine possible radial concentration gradients at the bottom of the column.

The gas sampling ports consisted of brass filters connected by 3-mm copper tubes to bulkhead fittings on the aluminum pipe. Additional 3-mm copper tubing led to the sampling points at the top of the column. These points had fittings for connection to Lucas Cell radon samplers, and were kept sealed when not in use.

The moisture sensors at the Salt Lake City and Mexican Hat sites were electrical resistance devices with a porous fiberglass binding which served as the interface with the moist soil (MC-360, Soiltest, Inc., Evanston, Ill.). These devices also contained an electrical-resistance temperature sensor. The moisture sensors at the Grand Junction site were gypsum block sensors, with a similar mode of electrical operation to that for the fiberglass devices. Separate thermocouple temperature sensors were installed at Grand Junction.

After installing the sampling devices on the aluminum pipes, each was buried in the tailings to within 91-cm (3 ft) of its top. Sixty-one centimeters (2 ft) of tailings were then compacted into the open bottom of each column to provide a defined radon source region which minimized radial diffusion at the bottoms of the columns. Tailings were also bermed up around the sides to within approximately 15-cm (6 inches) of the top. A thin layer of cover soil was placed over the top of the surrounding tailings to reduce windblown contamination.

2.2 COVER SOILS

The soils which were added to each of the test columns were locally available materials purchased from commercial sources. The soil at Salt Lake City was a silty clay-aggregate obtained from the southwest part of Salt Lake Valley, about 8.5 miles from the site. The soil at Mexican Hat was a fine to medium sand with a trace of silt, located adjacent to the pile. The Grand Junction covers utilized the "adobe clay," which was used in the 1981 joint field tests. This material is primarily highly weathered Mancos shale. The compaction characteristics of these soils are indicated by the standard Proctor test results in Table 2-1.

TABLE 2-1
STANDARD PROCTOR TESTS ON TAILINGS COVER SOILS

	<u>Max. Dry Density (g/cm³)</u>	<u>Optimum Moisture (dry wt. percent)</u>
Salt Lake City	1.9	13.2
Mexican Hat	2.02	11.0
Grand Junction	1.87	13.9

The soil was added to each test column in 20-25 cm (8-10 inch) lifts and mixed with a small amount of water, as necessary, to achieve an in-place moisture near that moistures in similar undisturbed soils in the area. The soil for the Salt Lake City column required a little water only for mixing with a dry surface crust. At Grand Junction and Mexican Hat, the soil was all very dry and dusty. Water was therefore added to assist in compaction and to achieve moisture levels thought to be those that would remain when the cover equilibrated. The soil was compacted with a pneumatic tamper (pogo stick). Excessive compaction was avoided.

Soil samples were taken periodically during cover installation to determine the moisture content and density at which the covers were applied. Some of these samples were also used to estimate the radium contents of the tailings and cover materials. Table 2-2 lists the results of the cover density and moisture measurements. As indicated, identical dry densities were achieved despite varying moisture contents. These were below the 90-95% of standard proctor densities achievable in larger field applications. The mean radium contents in the tailings and cover materials are listed in Table 2-3. The radium contents showed no significant trends with depth.

TABLE 2-2
INITIAL COVER DENSITIES AND MOISTURES
IN TEST COLUMNS

	<u>Bulk Dry Density (g/cm³)</u>	<u>Relative Compaction (% of Std. Proctor)</u>	<u>Initial Moisture Content (dry wt. percent)</u>
Salt Lake City	1.6 ± 0.1	84	16.6
Mexican Hat	1.6 ± 0.1	79	8.0
Grand Junction			
305 cm	1.6 ± 0.1	86	9.1
Grand Junction			
427 cm	1.6 ± 0.1	86	7.4

TABLE 2-3
RADIUM CONTENTS OF TAILINGS AND TEST COVERS

	<u>Tailings Radium (pCi/g)</u>	<u>Cover Radium (pCi/g)</u>
Salt Lake City	700 ± 190	0.73
Mexican Hat	640 ± 70	0.87
Grand Junction	1400 ± 90	1.71

Prior to emplacement of the cover material, the empty aluminum columns were left undisturbed for one month at Grand Junction and Mexican Hat. This provided an interval for equilibration and measurement of the radon fluxes from the bare tailings surfaces at the bottom of the columns. At the Salt Lake City site the bare tailings flux measurements were prevented by the infiltration of water into the test column. The cover was therefore installed shortly after insertion of the aluminum column.

3. RADON FLUX AND MOISTURE DATA COLLECTION AND INTERPRETATION

The field test columns were monitored in two phases. The first phase was aimed at characterizing the bare tailings source and the second was aimed at characterizing the radon movement through the cover. During the first phase, only radon flux measurements were conducted. The second phase additionally included radon concentration profile measurements, moisture measurements and temperature measurements. The following sections describe these measurements and the resulting data.

3.1 INITIAL RADON FLUXES

During the one-month period between preparation of the tailings source and application of the cover soil, radon fluxes were measured from the bare tailings surfaces at Grand Junction and Mexican Hat. The flux measurements utilized small charcoal cartridge (type GMA) radon flux samplers which have been described previously (Ni81), and also a large-area charcoal-type sampler. The large-area sampler, (LAS) covered an area of 0.16 m^2 , compared to 0.005 m^2 for the small sampler, but was otherwise similar in design. Both samplers had an approximate 1 cm layer of charcoal at ground level covering the entire sampling area, and minimized the air-filled void volume in the sampling device.

The radon fluxes measured with these samplers are summarized in Table 3-1. Because of the larger area represented by the LAS measurements, these fluxes are preferred over the GMA fluxes. Higher fluxes were observed after the initial excavations for the test columns, but the fluxes in

Table 3-1 represent the steady-state fluxes just prior to the cover installation. The 20-fold lower source flux at Mexican Hat arises from the factor of two lower radium content in Table 2-3 and from the smaller tailings thickness at the Mexican Hat site.

TABLE 3-1
RADON FLUXES MEASURED ON BARE TAILINGS AT THE BOTTOMS
OF THE GRAND JUNCTION AND MEXICAN HAT TEST COLUMNS

<u>Column</u>	<u>Date</u>	<u>Average Radon Flux (pCi/m²)</u>	
		<u>GMA^a</u>	<u>LAS^b</u>
Grand Junction			
10 ft	8/20/81	1870	2380
14 ft	8/20/81	1390	1980
Mexican Hat	9/11/81	68	99

a 0.0054 m² sampling area.

b 0.16 m² sampling area.

3.2 RADON FLUXES IN THE VICINITY OF THE COLUMNS

Radon fluxes from undisturbed tailings surfaces were measured in the vicinity of each of the test columns. These fluxes are summarized in Table 3-2. The flux at the Grand Junction site was actually measured about fifty yards away, and may not be the same as the flux in the immediate vicinity of the columns. At Mexican Hat, the flux is similar to that measured at the bottom of the test column (Table 3-1). The surface flux near the Salt Lake column is higher than would be expected for the bottom of the test

column because of the saturated conditions in the tailings at depth. The radon flux for Salt Lake City in Table 3-2 can thus be regarded as an upper limit for the source flux for the test column at this site.

TABLE 3-2
RADON FLUXES FROM BARE TAILINGS SURFACES IN THE VICINITY OF THE COLUMNS

<u>Site</u>	<u>Average Flux (pCi/m²sec)</u>
Salt Lake City	176
Mexican Hat	81
Grand Junction	770

3.3 RADON FLUXES THROUGH THE TEST COVERS

Radon fluxes were measured from the top surface of the covers on each of the test columns, as shown in Figure 2-1, at several times throughout the following year. These measurements are summarized in Table 3-3. Again, the samples collected by the large-area sampler (LAS) are considered more representative because of the improved precision associated with the larger sampling area. As indicated by the data, the fluxes at both Salt Lake City and Mexican Hat were below 20 pCi/m². Those at Grand Junction were both higher, in part because of the much higher source fluxes for these test columns.

3.4 SOIL MOISTURE AND TEMPERATURE PROFILES

Soil moistures were calculated from the electrical resistance

TABLE 3-2
RADON FLUXES FROM THE SURFACES OF THE TEST COVERS

<u>Column</u>	<u>Date</u>	<u>Radon Flux (pCi/m²s)</u>	
		<u>GMA^a</u>	<u>LAS^b</u>
Salt Lake City	09/08/81	1.0	1.8
	10/10/81	1.0	0.5
	10/29/81	1.9	0.9
	02/25/82	3.1	0.9
	03/25/82	2.3	0.4
	05/25/82	0.8	0.4
	05/12/82	2.2	---
	Mean	1.8 ± 0.9	0.8 ± 0.5
Mexican Hat	03/03/82	22.2	11.7
	05/13/82	2.8	5.8
	07/21/82	14.0	10.6
	Mean	13 ± 10	9.4 ± 3.1
Grand Junction 10-ft.	09/30/81	299	293
	03/05/82	142	337
	05/13/82	362	192
	07/21/82	---	194
	Mean	270 ± 110	250 ± 70
Grand Junction 14-ft.	09/30/81	110	86
	03/05/82	104	88
	05/13/82	139	142
	07/21/82	81	92
	Mean	110 ± 20	100 ± 30

a 0.0054 m² sampling area
b 0.16 m² sampling area

measurements with the fiberglass or gypsum blocks using laboratory calibration curves. The curves were generated from resistance and moisture measurements with matching sensors in laboratory samples of each of the three soils. Although the laboratory calibrations were performed at approximately the same soil compactions as the field columns, exact correspondence was not achieved. The resulting calibration curves were therefore normalized to field grab samples taken at depths corresponding to several of the moisture sensors. The soil moisture profiles calculated for each of the test columns are presented in Tables 3-4 - 3-6. The profiles at Salt Lake City (Table 3-4) show the saturated zone near the bottom, with lower moistures near the top. Heavy spring rains also caused high moistures in several of the upper measurements. The profiles at Mexican Hat (Table 3-5) and Grand Junction (Table 3-6) show lower moistures and less variation with depth.

Soil temperatures were measured with thermistors located in the moisture sensors at the Salt Lake City and Mexican Hat sites. The resulting temperature profiles (Tables 3-4 and 3-5) document the seasonal variations in surface soil temperature gradients, which can be driving forces for moisture and gas transport. The mathematics describing these transport processes are complicated and are not well-developed, and calculations quantifying these effects were not performed. At both of these sites, temperatures at the bottoms of the columns exhibited much less variation than those closer to the surface. Temperatures in the Grand Junction columns were not measured.

TABLE 3-4

SOIL MOISTURE AND TEMPERATURE PROFILES AT SALT LAKE CITY
(dry weight percent)
(°C)

Depth (ft)	<u>9/8/81</u>	<u>10/29/81</u>	<u>12/21/81</u>	<u>2/25/82</u>	<u>3/24/82</u>	<u>5/25/82</u>	<u>6/12/82</u>
2	22% 22°	5% 12°	5% 6°	8% 6°	21% 4°	21% 14°	21% 15°
5	4% 22°	4% 15°	4% 9°	4% 9°	4% 6°	5% 11°	5% 13°
8	23% 19°	8% 16°	7% 12°	8% 12°	8% 8°	9% 10°	9% 11°
11	23% 15°	21% 14°	23% 12°	23% 12°	23% 9°	23% 10°	23% 9°
13	26% 13°	24% --	26% 12°	26% 12°	26% 10°	26% 9°	26% 9°

TABLE 3-5

SOIL MOISTURE AND TEMPERATURE PROFILES AT MEXICAN HAT
(dry weight percent)
(°C)

Depth (ft)	<u>3/2/82</u>	<u>5/13/82</u>	<u>7/19/82</u>
1	4% 8°	4% 16°	5% 30°
4	4% 9°	4% 16°	5% 24°
7	3% 11°	3% 14°	5% 20°
10	5% 13°	5% 14°	5% 18°
13	6% 13°	6% 14°	6% 17°

TABLE 3-6
SOIL MOISTURE PROFILES AT GRAND JUNCTION
(dry weight percent)

14 Foot Column

<u>Depth (ft)</u>	<u>9/30/81</u>	<u>3/4/82</u>	<u>5/12/82</u>	<u>7/20/82</u>
1	14	11	7	18
4	8	14	7	5
7	7	6	5	7
10	5	4	4	15
13	--	--	--	14

10 Foot Column

2	4	7	6	9
4	4	6	6	12
6	10	8	7	11
9	17	--	--	--

3.5 RADON FLUX DATA INTERPRETATION

The effectiveness of the earthen covers was evaluated quantitatively by computing radon diffusion coefficients from the radon flux field data in Tables 3-1 and 3-3. These diffusion coefficients are presented in Table 3-7 for the Mexican Hat and Grand Junction sites. A diffusion coefficient for the Salt Lake City site could not be calculated from the flux comparison because a representative bare source flux for this site could not be measured.

Laboratory measurements of radon diffusion coefficients were also performed for the three soil materials. These coefficients are also listed in Table 3-7. As indicated, the laboratory measurements had slightly different moistures and densities from those in the field test columns. The laboratory diffusion coefficients were therefore normalized to the field moisture and compaction conditions using a simple correlation (Ro82a) of laboratory diffusion coefficients with moisture and porosity. These normalized diffusion coefficients are also listed in Table 3-7, along with diffusion coefficients predicted solely from the correlation equation. The correlation equation used for these estimates is

$$D = 0.07 \exp[-4(m - mP^2 + m^5)] , \quad (1)$$

where

D = diffusion coefficient for radon in the soil pores (cm²/s)

m = volume fraction of moisture saturation

P = soil porosity

As indicated by the comparisons in Table 3-7, the agreement between

TABLE 3-7

COMPARISON OF DIFFUSION COEFFICIENTS CALCULATED FROM FLUX DATA
WITH LAB MEASUREMENTS AND CORRELATION PREDICTIONS

	J_0 ($\text{pci}/\text{m}^2\text{s}$)	J ($\text{pci}/\text{m}^2\text{s}$)	Cover Moisture (dry wt %)	Bulk Density (g/cm^3)	Radon Diffusion Coeff., D (cm^2/s)
<u>Salt Lake City</u>					
Field Measurements	--	0.8 ± 0.5	22.7 ^a	1.6	--
Lab Measurements ^b			14.4	1.5	0.0074
Norm. Lab Measurements ^c			22.7	1.6	0.00034
Correlation ^d			22.7	1.6	0.00038
<u>Mexican Hat</u>					
Field Measurements	99	10 ± 3	4.7	1.6	0.036
Lab Measurements			6.9	1.88	0.013
Norm. Lab Measurements			4.7	1.6	0.035
Correlation			4.7	1.6	0.038
<u>Grand Junction - 10 ft</u>					
Field Measurements	2380	254 ± 73	8.2	1.6	0.024
Lab Measurements			8.0	1.67	0.0129
Norm. Lab Measurements			8.2	1.6	0.015
Correlation			8.2	1.6	0.024
<u>Grand Junction - 14 ft</u>					
Field Measurements	1980	102 ± 27	8.6	1.6	0.029
Lab Measurements			8.6	1.6	0.014
Correlation			8.6	1.6	0.022

a Moisture content of only the lower soil layer at Salt Lake City, due to moisture gradient. Other moistures are averaged over entire cover.

b Laboratory measurements used the small-sample transient-diffusion technique.

c Normalized to field moisture and compaction using the diffusion coefficient correlation.

d Correlation equation: $D = 0.07 \exp[-4(m - \text{mp}_2 + \text{m}^5)] \text{ cm}^2/\text{s}$.

the field-measured diffusion coefficients and those predicted solely from the correlation was very good. The average relative difference between the field-measured coefficients and the correlation predictions was less than ten percent. The normalized laboratory coefficients differed by about 31 percent from the field measured coefficients. This larger difference was dominated by the lab measurement with the Grand Junction soil, which had the largest moisture difference from the field moistures. For the Salt Lake City site, the laboratory measurement and the correlation provide consistent estimates of the diffusion coefficient despite the lack of data for a diffusion coefficient based on radon fluxes. The correlation given in Equation 1 is therefore demonstrated to be a useful estimator of radon diffusion coefficients from standard soil parameters which are generally available.

4. ADDITIONAL RADON MEASUREMENTS AND INTERPRETATIONS

The radon flux data and interpretations in the previous chapter meet the objectives of the benchmark tests; however, additional radon data were obtained in order to obtain maximum benefit from these field experiments. The additional data consist of radon gas concentration profiles in each of the test columns, and are given in this chapter, along with comparisons with the expected concentrations calculated from the measured diffusion coefficients in Table 3-7.

4.1 RADON CONCENTRATION PROFILES

Radon gas concentration profiles were measured by drawing soil gas from the sampling tubes in each of the test columns. The gas was sampled directly into evacuated Lucas cells, and was subsequently counted for radon and daughter alpha activity. The radon concentrations calculated from the alpha activities in the soil gas are summarized in Tables 4-1 - 4-3. Data were not obtained from several of the sampling ports because of sampling difficulties. In most cases, these were caused by plugged or damaged sampling ports. In addition, the Vitro site in Salt Lake City tended to have water saturating the tailings around the lowest sampling port because of the variable high water table. The resulting two measurements at the 13 foot depth in Table 4-1 are therefore low because of the inability to draw a sufficient volume of soil gas from the sampling ports.

A comparison of the radon concentration profiles at Salt Lake City and Mexican Hat shows very different degrees of radon diffusion through the

TABLE 4-1
RADON GAS CONCENTRATION PROFILES AT SALT LAKE CITY
(pCi/cm³)

	<u>2 ft</u>	<u>5 ft</u>	<u>8 ft</u>	<u>11 ft</u>	<u>13 ft</u>
9/8/81	0.37	0.57	1.10	98.8	141 ^a
10/9/81	--	.25	--	--	--
10/29/81	0.45	.62	1.10	--	154 ^a
12/21/81	--	.59	0.74	--	--
2/25/82	--	.56	.80	--	--
3/24/82	0.69	.66	.75	74.4	--
5/25/82	0.32	.49	.57	54.5	--
6/12/82	0.16	.17	.55	73.5	--
Mean	0.40	0.49	0.80	75.0	148 ^a
<u>±</u> Standard Dev.	<u>±</u> .19	.18	.22	18.0	9

a Incomplete sample collection.

TABLE 4-2
RADON GAS CONCENTRATION PROFILES AT MEXICAN HAT
(pCi/cm³)

	<u>1 ft</u>	<u>4 ft</u>	<u>7 ft</u>	<u>10 ft</u>	<u>13 ft</u>	<u>13 ft^a</u>
3/3/82	5.3	15.9	44	84	204	182
5/13/82	6.2	15.6	23	82	129	151
7/19/82	4.1	--	19	63	121	169
Mean	5.2	15.8	29	76	151	167
+ Std. Dev.	1.1	.2	13	12	46	16

^a Concentrations outside of test column in surrounding tailings.

TABLE 4-3
RADON GAS CONCENTRATION PROFILES AT GRAND JUNCTION
(pCi/cm³)

	<u>14 ft Column</u>			<u>10 ft Column</u>			
	<u>4 ft</u>	<u>7 ft</u>	<u>10 ft</u>	<u>2 ft</u>	<u>4 ft</u>	<u>6 ft</u>	<u>9 ft</u>
9/30/81	189	--	--	0.38	16.9	--	1119
3/4/82	190	367	672	0.30	--	346	1068
5/13/82	161	332	540	0.84	9.6	287	971
7/21/82	174	358	693	--	--	325	--
Mean	179	352	635	0.51	13	319	1053
+ Std. Dev.	14	18	83	.29	5	30	75

cover. In the case of the Salt Lake City column, virtually all of the radon has been contained beneath the 8 ft level, while at Mexican Hat, appreciable radon is indicated to be penetrating the entire cover. The 14 ft column at Grand Junction similarly has relatively high radon concentrations throughout the cover depth, with a depletion near the top surface due to radon escape into the atmosphere. The 10 ft column at Grand Junction (Table 4-3) had similar radon concentrations at the 6 ft depth to those in the adjacent 14 ft column, but had significantly lower concentrations at the 2 and 4 ft depths. The radon concentrations in the tailings at Grand Junction were much higher than those at Salt Lake City or Mexican Hat, because of their much higher radium content (Table 2-3) and emanation coefficient (Ro82a).

A quantitative interpretation of the radon concentration profile data in Tables 4-1 - 4-3 was made by comparing the measured profiles with calculated radon profiles. The calculated profiles were determined using the measured radon diffusion coefficients reported in Table 3-7. As was done previously, the laboratory diffusion coefficients were normalized to the field moisture and density conditions for use in these calculations. Other data used in the calculations include the radium concentrations in Table 2-3, and emanation coefficients determined previously for these tailings (Ro82a). Since moistures were measured at different depths for each column, these moisture profiles (Tables 3-4 - 3-6) were used to generate diffusion coefficient profiles by normalizing the measured laboratory diffusion coefficients to the moistures in each layer using Equation 1. Since diffusion coefficients were not measured for the tailings materials, the required tailings diffusion coefficients were estimated solely from

Equation 1.

Radon concentration profiles were calculated from the above parameters using the RAECO computer code (Ro81). Each cover system was broken into several layers as defined by the varying moistures and diffusion coefficients. Because the measured data are radon concentrations in the soil gas only and not in the total pore space, RAECO was modified as required (Ro82b) to calculate the soil gas concentrations and relate them to the diffusion coefficients for the total pore space.

The resulting radon concentration profiles are plotted in Figures 4-1 - 4-4 for comparison with the measured concentration profiles. In general the agreement is excellent between the field measured radon concentrations and the concentrations calculated with RAECO using laboratory diffusion coefficients, radium contents and emanating powers.

As indicated in Figure 4-1, the radon concentration profile calculated for the Salt Lake City column is in excellent agreement with the four measured data points. The radon concentrations in the upper part of the cover result predominantly from the 0.7 pCi/g radium in the cover (Table 2-3). The radon flux calculated by RAECO from the radon concentration profile calculation in Figure 4-1 was 0.3 pCi/m²s, which nominally agrees with the measured radon flux of 0.8 ± 0.5 pCi/m²s (Table 3-7).

The radon concentration profile calculated for Mexican Hat in Figure 4-2 is also in excellent agreement with the measured radon concentration profile at all five measured points. In this case, the 0.9 pCi/g radium in the cover had little contribution to the larger quantity of radon diffusing upward from the tailings. The radon flux calculated by RAECO from the radon concentration profile calculation was 16 pCi/m²s in this

FIGURE 4-1. COMPARISON OF MEASURED AND CALCULATED RADON CONCENTRATION PROFILES FOR THE SALT LAKE CITY TEST COLUMN.

FIGURE 4-2. COMPARISON OF MEASURED AND CALCULATED RADON CONCENTRATION PROFILES FOR THE MEXICAN HAT TEST COLUMN.

FIGURE 4-3. COMPARISON OF MEASURED AND CALCULATED RADON CONCENTRATION PROFILES FOR THE 14 FOOT COLUMN AT GRAND JUNCTION.

FIGURE 4-4. COMPARISON OF MEASURED AND CALCULATED RADON CONCENTRATION PROFILES FOR THE 10 FOOT COLUMN AT GRAND JUNCTION.

case, again in nominal agreement with the measured fluxes of 10 ± 3 pCi/m²s (Table 3-7).

The radon concentration profile calculated for the Grand Junction 14 ft column in Figure 4-3 is also in excellent agreement with the three measured data points. Again in this case, the 1.7 pCi/g radium in the cover had negligible effect. The radon flux calculated for the illustrated concentration profile was 78 pCi/m²s, agreeing with the average measured radon flux 102 ± 27 pCi/m²s (Table 3-7).

The radon concentration profile calculated for the Grand Junction 10 ft column in Figure 4-4 is in good agreement with the 6 and 9 ft concentrations. It also yields a radon flux, 190 pCi/m²s, which agrees with the measured flux, 254 ± 73 pCi/m²s in Table 3-7. These data suggest that the concentrations at 2 and 4 ft depths for this column are in error, since they are inconsistent with the other radon concentrations, the measured diffusion coefficients and moistures, and the measured radon flux. Comparison of the 2 ft radon concentration with the measured flux would suggest a diffusion coefficient for the soil larger than that for pure air. It is hypothesized that the sampling ports for these two depths were partially obstructed, yielding an incomplete gas sample under normal sample collection procedures.

In summary, the measured radon gas concentration profiles were approximated with very good accuracy using the measured laboratory source parameters (radium concentrations and emanation coefficients), the laboratory measurements of the diffusion coefficients, and the computer code RAECO. The measured and calculated radon fluxes were also shown to be consistent with the measured and calculated radon concentration profiles.

Thus, the extra effort of measuring and calculating radon soil gas concentration profiles lends strong support to the validity of the laboratory measurements and calculational tools used in this study.

5. IMPLICATIONS OF THE BENCHMARK TESTS

The field benchmark tests have demonstrated that significant reduction in radon fluxes can be achieved with simple earthen covers, even without reliance on special cover designs, engineered materials, or high soil compactions. The data from the Salt Lake City site indicate that when the water table is unusually shallow, very high moistures can be maintained in the earthen covers. The resulting diffusion coefficients for radon were on the order of 3×10^{-4} cm²/s for this soil region, and would thus require minimal cover thickness (0.5 m) to achieve a flux of 20 pCi/m²s, if soil moisture levels are maintained.

Much higher diffusion coefficients for radon were demonstrated in the drier climates of Mexican Hat and Grand Junction. The cover soils used at these sites were also low in clay contents, and were thus not favorable for moisture retention. At the Mexican Hat site, where the source flux was about 100 pCi/m²s, however, the 3.66 m cover was very adequate to reduce the radon flux by a factor of ten. It is estimated that less than 1 m of cover with identical properties would achieve a 20 pCi/m²s radon flux.

The Grand Junction covers had a slightly lower radon diffusion coefficient than the Mexican Hat cover, but did not achieve the desired radon flux limit because of the 20-fold higher source flux at this site. It is estimated that, if the unconsolidated adobe clay were used as a cover, 5.4 m of it would be required to reduce the radon flux to 20 pCi/m²s at this site.

It should be noted that all of the present cover systems were evaluated at compactions less than would be utilized in actual field

applications. Densities of 90-95% of Proctor are routinely achievable in earth-moving projects without significant cost penalties, and could be expected in any reclamation of uranium tailings piles. The higher densities tend to promote greater moisture retention in earthen covers, and more importantly, a higher degree of moisture saturation and a lower diffusion coefficient. This improves the performance of earthen covers. The present tests were therefore conservative in this respect in their evaluation of earthen cover performance.

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