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**LABORATORY RESEARCH ON TAILINGS
STABILIZATION METHODS AND THEIR
EFFECTIVENESS IN RADIATION CONTAINMENT**

APRIL 1978

PREPARED FOR

**UNITED STATES DEPARTMENT OF ENERGY
GRAND JUNCTION, COLORADO
CONTRACT NO. E(05-1)-1658**

BY

Ford, Bacon & Davis Utah Inc.

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By

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ABSTRACT

This report describes a study of various methods, techniques, and materials for stabilizing uranium mill tailings to reduce radon exhalation.

Radon emanation from tailings particles, radon exhalation from tailings, and methods that could be used to reduce radon exhalation from tailings piles are discussed. Surface radon flux and soil gas concentrations were measured in experiment chambers or columns consisting of uranium tailings and various types and thicknesses of cover materials. The applicability of diffusion theory was examined and effective diffusion coefficients were determined for clay, soil, and sand. The variation of radon flux with atmospheric effects and moisture also was investigated.

The effectiveness of several types of chemical stabilizers for both volumetric and surface application in reducing radon exhalation is reported. Some volumetric stabilizers reduced radon flux by 90% or more.

Radon flux was determined through the use of charcoal gas mask canisters, and flux accumulation chambers sampled by Lucas cells. Both of these techniques are described. Soil gas concentration was sampled with Lucas cells and counted with a sodium iodide scintillation spectrometer system.

Emanating power of uranium tailings was measured for several particle sizes and found to be relatively constant at about 20%.

Two types of grasses were found that would grow in tailings if sufficient water and fertilizer were provided. The effect of vegetation on radon exhalation was not determined.

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CHAPTER 1
INTRODUCTION

CHAPTER 1

INTRODUCTION

The milling of uranium ore produces large quantities of solid residues in the form of radioactive tailings. The quantities are large because the concentration of uranium initially in sandstone mineral deposits is low, of the order of 0.05 to 0.4 weight percent,⁽¹⁾ and only the uranium is removed when the ore is processed. This low concentration, however, is at least a factor of 1,000 times larger than the average concentration of uranium in the earth's crust.

The tailings are radioactive because the extracted uranium was initially in equilibrium with all its radioactive decay products and these decay products remain with the tailings. The decay chain of the uranium isotope ^{238}U , which constitutes 99.3% of natural uranium, is presented in Figure 1-1. Because the uranium in ore is concentrated at least 1,000 times over the average concentration in the earth's crust, the radioactive decay products which remain with the tailings are also concentrated.

One of the most significant sources of exposure to low level radiation from uranium mill tailings is associated with the ionizing radiation from the inert gas ^{222}Rn , a daughter of ^{226}Ra , and from ^{222}Rn daughters. Radon concentrations in air that were in excess of background values have been detected at distances greater than 1,000 m from tailings piles.^(2,3) The primary purpose of this study is to characterize and quantify the release of radon gas from uranium mill tailings. A second purpose has been to investigate methods which could be used to confine or retard the release of radon until it can decay within the confines of the tailings pile or covering material.

To characterize and quantify the release of radon gas and investigate the methods to confine it, the following specific tasks were accomplished:

Task I - Design and construction of test chambers built to measure radon gas concentration in tailings and cover material. Surface flux was measured for varying thickness of tailings plus tailings and cover material combinations. This task verified the applicability of diffusion theory and determined effective diffusion coefficients for the materials used. The self-shielding of tailings was also determined as part of this task.

Task II - Investigations of atmospheric effects on radon exhalation from tailings including pressure, temperature, wind, and moisture.

⁽¹⁾ See end of chapter for references.

Task III - Measurements performed of the flux reduction from application of chemical stabilizers to tailings surfaces. Stabilizers included foams, epoxies, and asphaltic emulsions which may be used as alternative cover materials for radon flux reduction in addition to soil stabilization.

Task IV - Measurements of the flux reduction from applying volumetric chemical stabilizers. This task was similar to Task III and the radon reduction and soil stabilization characteristics were determined.

Task V - Investigations of vegetative stabilization of mill tailings to determine extent of root penetration into tailings and applicability as an agent to reduce or prevent erosion.

Task VI - Measurements of the emanating power of tailings for both a composite sample and for samples which had been segregated according to particle size. The emanating power is an important parameter in modeling the radon source for concentrations and flux calculations.

Task VII - Measurements of the amount of gamma-ray build-up due to radon daughters precipitating out in clean cover material to determine if extra cover material might be required to reduce gamma dose rates above tailings.

Methods for accomplishing the foregoing tasks were developed to (a) provide for accurate and specific information of value in assessing radon gas migration and attenuation of surface exhalation, and (b) to lead to a basic understanding of the radon exhalation process. The results of the above tasks are reported in this document.

FIGURE 1-1. RADIOACTIVE DECAY CHAIN OF URANIUM-238

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CHAPTER 2
PREVIOUS RADON STUDIES

CHAPTER 2

PREVIOUS RADON STUDIES

As early as 1935, Harrison^(1,2) performed experiments to measure diffusion of radon gas mixtures. In 1945, Kovach⁽³⁾ reported measurements of meteorological effects upon radon soil-gas concentrations. His experiments, using pipes buried to different depths in the ground and ionization chambers to measure the radon concentration, showed that long periods of snow and ice covering cause the underground concentrations at various depths to approach the same value. He also noted that wind and barometric changes caused noticeable effects while effects due to temperature could not be distinguished.

During the 1950's, studies were performed to determine radon leakage,⁽⁴⁾ distributions of radon and other radioactive products above and below ground,⁽⁵⁾ and factors which influence the permeability and diffusion of radon in synthetic sandstone.⁽⁶⁾ These studies indicated a diffusion constant for radon of 9×10^{-3} to 5×10^{-2} cm²/sec depending upon the permeability and density of the sandstone and radon leakage of 0.1% to 27% depending on the material tested.

During the early 1960's, Kraner, Schroeder and Evans^(7,8) performed significant measurements of the effect of atmospheric variables on radon exhalation and concentration in soil. These measurements, which were performed in Lincoln, Massachusetts and on the Rainier Mesa at the Nevada Test Site, included barometric, precipitation, and wind effects. Because these experiments were performed in uncontrolled conditions, little attempt could be made to separate the effects which result from simultaneous changes of atmospheric conditions such as pressure and winds. The results of Kraner's experiments demonstrate the "capping effect" of precipitation in which moisture effectively traps or absorbs the radon gas. Further, pressure effects were interpreted as transport phenomena in which pressure acted as the force to "pull or push" the radon from the ground.

More recently, Culot, Schiager et al.⁽⁹⁻¹¹⁾ have performed studies related to the diffusion of radon in tailings, cover soil, and concrete. These studies were more quantitative in nature and provide a basis for the work performed here. Their results of phenomenological studies determined the effective diffusion coefficient to be 5×10^{-2} cm²/sec with a radon relaxation length of 1.54 m in soil. Relaxation length is defined as the thickness of cover material required to reduce the radon concentration to a fraction (1/e) of its original value. As defined by Culot,⁽¹¹⁾

(1) See end of chapter for references.

the relaxation length equals D/λ , where D is the effective diffusion coefficient and λ is the decay constant.

Wilkening et al.⁽¹²⁾ have performed measurements of the radon flux at the earth-air interface over much of the earth and correlations with atmospheric effects were attempted. Their results indicate meteorological influences on radon exhalation are minor and that the flux is predominantly determined by the characteristics of the soil. Other results show that the radon flux from lava, oceans, and ice fields is very small compared to other regions of large land mass. These results have also been noted by others.⁽¹³⁾

Tanner⁽¹⁴⁾ has presented a review of radon emanation and diffusion characteristics prior to 1964. The results of some articles referenced in the review indicate the mobility of radon precursors and that discrimination between radon and its precursors is possible. The diffusion coefficient of radon is also given in the range 7×10^{-3} for varied clays to 6.8×10^{-2} cm²/sec for building sand. Also, the diffusion coefficient for radon in mud was approximately 3×10^{-6} cm²/sec.

Stabilization of mill tailings against erosion due to wind and water has been partially successful in the Western United States. Studies indicate that some problems do exist with respect to root penetration and possible uptake in the plants.⁽¹⁵⁻¹⁸⁾

The use of asphaltic stabilizers also have been investigated for the ability to retard radon exhalation on tailings piles.⁽¹⁹⁾ The study indicated that asphaltic emulsions may be an effective means of reducing radon exhalation due to the small measured diffusion coefficient of 1.2×10^{-7} cm²/sec for radon in the emulsion.

Various polymeric materials also have been studied for their effectiveness as a radon sealant in uranium mines.^(20,21) The leaching of tailings to remove radium also has been investigated^(22,23) as a means of reducing the environmental impact of the tailings.

The above references provide a sampling of background research which has been performed to develop an understanding of radon and its control. This review does not present all research, but includes the most significant work that has been done.

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CHAPTER 3

EXPERIMENTAL PROCEDURES AND EQUIPMENT

CHAPTER 3

EXPERIMENTAL PROCEDURES AND EQUIPMENT

Two basic sampling techniques, using Lucas cells and charcoal canisters, were employed in this study to determine radon gas concentrations and radon fluxes. Gamma-ray buildup in cover material was determined with a sodium iodide scintillator counting system. Similar techniques have been used previously and reports of the procedures used are available.^(1,3) Modifications of these techniques were used for the present experimental arrangement; and these modifications are described below.

3.1 Radon Concentration Determination Using Lucas-Type Cells

Early experiments to determine the effects of radiation on man led to the development of the Lucas cell for measuring small amounts of alpha-active radon gas.⁽³⁾ The Lucas cell, a bell-jar-shaped container coated on the interior wall with silver activated zinc sulfide, is filled with air containing radon gas. When alpha particles from radon and radon daughters strike the zinc sulfide it emits photons some of which pass through a clear window in the bottom of the cell and are detected by a photomultiplier (PM) tube. The PM tube produces current pulses that are counted by the appropriate electronics.

Two standard cells of different manufacture were used in this study, as well as larger volume flow-through flasks. The first, a standard commercial Lucas cell, had an effective volume of 100 ml and an average overall counting efficiency of 83%. The second type of cell was made by project personnel by coating the entire interior walls of 150 ml Erlenmeyer flasks with activated zinc sulfide. These provided an overall efficiency approximately one half that of the commercial cells. Both types of cells were fitted with stopcocks through which the cells could be evacuated and the gas samples introduced.

The flow-through-type flasks were 500 ml in volume, and had two stopcock valves in the clear plastic body which was lined with zinc sulfide film.

3.1.1 Sampling and Counting of Radon Gas

Sampling of radon gas is accomplished with a Lucas cell that has been evacuated using any typical vacuum pump capable of attaining absolute pressures of approximately 10 to 50 microns. The gas sample is then introduced into the cell through an A/E-type Gelman filter to avoid obtaining extraneous counts from alpha active airborne particulates. The cell is stored after sampling

(1) See end of chapter for references.

while the radon gas comes to secular equilibrium with its daughter products through ^{210}Pb , usually for 3 to 4 hours. The gross alpha activity of the cell is then measured with the counting system described in paragraph 3.1.2 and the concentration is calculated using the equation given in paragraph 3.1.3. Postcounting evacuation and flushing using aged dry air is performed to reduce the amount of radon daughters which attach to the walls of the cell and increase the background of the cell.

3.1.2 Electronic Counting Equipment

The Lucas cells were counted using either a 7.6- or 12.7-cm diameter PM tube connected to a Ludlum 2200 Scaler/Timer. The efficiencies determined for the cells included losses in the PM tube and counting circuitry. Figure 3-1 shows the scaler/timer, 7.6 cm PM tube, a commercial Lucas cell, a project-made cell, and flow-through flask. The scaler/timer is equipped with variable threshold, high voltage and amplifier gain settings. Using a Lucas cell containing radon gas as a source for the PM tube, these settings were varied to obtain an appropriate operating point in the plateau response region where small voltage variations do not alter the counting sensitivity. Consistency of the counting efficiency was checked periodically using a Th-232 standard alpha source on a scintillation disk in the PM tube chamber.

3.1.3 Determination of the Concentration From Alpha Counting

After secular equilibrium of the radon daughters has been achieved, the total alpha particles counted in a detector during a time interval t to $t + \Delta t$ is given by

$$C_0 = \epsilon A_0 \int_t^{t + \Delta t} e^{-\lambda t} dt = \frac{\epsilon A_0}{\lambda} [e^{-\lambda t} - e^{-\lambda(t + \Delta t)}] \quad (1a)$$

where,

A_0 = initial radon activity (pCi)

C_0 = counts measured in the counting time Δt (counts)

Δt = counting period (hr)

t = elapsed time since sampling (hr)

λ = radon decay constant (hr^{-1})

Solving for the initial radon activity gives

$$A_0 = \frac{C_0 \lambda}{\epsilon [e^{-\lambda t} - e^{-\lambda(t + \Delta t)}]} \quad (1b)$$

Dividing by the volume of the sampling cell, the initial radon activity concentration is found to be

$$A = \frac{A_0}{V} \frac{C_0 \lambda}{\epsilon V [e^{-\lambda t} - e^{-\lambda(t + \Delta t)}] 1.33 \times 10^{14}} \quad (1c)$$

where,

V = the volume of sampling cell (l)

A = initial radon activity concentration (Ci/l)

1.33×10^{14} converts from disintegrations per hour to curies

3.1.4 Determination of Radon Surface Fluxes Using Lucas Cells

Radon surface fluxes can be determined using an accumulator drum sampled with Lucas cells as described by Wilkening.⁽⁴⁾ A relatively large volume container has its open end sealed to the surface across which the flux is to be measured. The initial radon gas concentration in this accumulation drum is the ambient background value. As time passes, the surface flux causes an increase in the radon concentration in the air in the drum. The increase in concentration is linearly proportional to the surface flux until the concentration becomes high enough to inhibit the flux by the reduced concentration gradient from the soil gas to the air. Sampling the gas in the drum every 1/2 hour through a sample port allows calculation of the flux measured using the times involved, the volume of the drum, and the buildup of radon concentration, by the relationship:

$$J = \frac{C V}{A t} \quad (2)$$

where,

J = radon surface flux (Ci/cm²-sec)

C = radon gas concentration above background (Ci/l)

V = accumulation drum volume (l)

A = area across which the flux measured (cm²)

t = time between sealing the drum to the surface and time the sample is taken (sec)

The sampling time must be short compared to the half life of radon and the time it takes for the change in concentration gradient to affect the flux.

3.1.5 Accuracy of Cell Measurements

The accuracy of the Lucas cell measurements is directly related to the counting statistics and the effective volume sampled. Inaccuracies in the volume sampled can come from incomplete evacuation of the cell before sampling or from termination of the sampling procedure before the gas pressure has come to equilibrium. Careful sampling techniques can reduce inaccuracies to counting statistics only.

The lower limit of detection of the Lucas cell measurements has been reported as approximately 1 pCi/l with long counting times and low backgrounds.⁽⁵⁾ The accuracy and precision of the method are reflected in several repeated determinations of cell efficiencies reported by Percival⁽⁶⁾ where the standard deviation of the efficiency was determined to be $\pm 1.2\%$ for many cells and $\pm 6\%$ for determinations on individual cells using standard radium solutions for calibration. Repeated efficiency measurements on this project indicate a precision of about $\pm 10\%$ for the cells produced by FB&DU.

3.1.6 Lucas Cell Efficiency

Lucas cell efficiencies for cells used in this study were determined using the deemanation method described by Percival⁽⁵⁾. Figure 3-2 shows the experimental arrangement. A radon bubbler is filled with a standard solution of radium in HCl acid with an activity of 9.77×10^{-7} mCi radium. The evacuated cell is attached to the system and stopcock 1 is opened. Stopcock 2 is slowly opened and the solution allowed to froth slowly until the system comes to equilibrium. The starting time of deemanation should be recorded. Stopcock 3 is opened slightly until the level of the bubbling liquid is approximately 2 in. above the natural level of the liquid. As the pressure equalizes, the frothing decreases and stopcock 3 may be opened slowly until it is open completely to atmospheric pressure. Deemanation is allowed to continue until only a few small columns of bubbles are rising through the solution. All stopcocks are then closed and the time is recorded. The cell is then allowed to achieve radioactive equilibrium before counting, approximately 3 to 4 hours; it is then counted for 1 hour.

The Lucas cell efficiency is then calculated as follows:

$$\epsilon = \frac{1.004c}{4.00 \times 10^{14} \times (1 - e^{-\lambda t_1}) \times e^{-\lambda t_2} \times 0.99 \times Ra \times V} \quad (3)$$

where,

1.004 = factor to correct for decay of radon-222 during a 1-hr count

c = net cph of sample minus net cph of blank corrected to same time as sample count

4.00×10^{14} = alpha dph/Ci of radon-222 and its daughters

Ra = activity of the standard solution (Ci/ml)

λ = disintegration constant for radon-222 (hr^{-1})

t_1 = time between deemanations allowing for ingrowth of radon-222 in the radium solution (hr)

t_2 = time between completion of deemanation and start of 1-hr count (hr)

0.99 = radium yield

V = sample volume (ml)

Once several cell efficiencies have been determined in this manner, the efficiencies of other cells can be determined by cross-comparison; sampling a large volume of known concentration with a few cells and comparing the results. The cell efficiencies, as determined by the above methods, are given in Table 3-1.

3.2 Radon Flux Measurements Using Activated Charcoal Canisters

Activated charcoal has been recognized and used as an effective means of trapping radon gas.^(1,2) Activated charcoal canisters of the U.S. Military M-11 and M-3 types have been used for radon flux measurements in this study. These canisters are displayed with the counting system in Figure 3-3. The canister on the left had part of the metal housing removed to increase the area for flux measurements. This type of canister has been used by the Health and Safety Laboratory (HASL)⁽¹⁾ and works satisfactorily.

3.2.1 Use of Charcoal Canisters for Flux Measurements

Basically, the activated charcoal in the canisters absorbs the radon gas that emanates from the surface over which the canister is placed. The radon is held by the charcoal and subsequently decays. After exposure to the radon emitting surface, the canister is stored for a minimum of 3 hr for equilibrium to be established between radon and its short-lived daughters. Then gamma-rays from the canister are counted using a well-shielded NaI detector and a pulse height analyzer (PHA) system to determine the integrated peak area for a specific gamma-ray energy. Then, the flux is calculated as described in the following section.

The precision of the method of determining the radon flux across the surface, by using activated charcoal canisters to accumulate radon gas, has been investigated and is discussed in paragraph 3.2.4. This method gives reliable flux measurements with a precision of approximately 15%. Accuracy is also on the order of 15%.

3.2.2 Determination of the Radon Flux Using the Bismuth-214 0.609-MeV Gamma-Ray

After equilibrium has been achieved, the activity of each radon daughter in the canister is equal to the radon activity; hence, the activity of the ^{214}Bi 0.609-MeV gamma-ray is proportional to the radon activity. The 0.609-MeV gamma-ray is relatively free of interfering radiation providing easy determination of the peak area. The 0.609-MeV gamma radiation was detected using a 12.7 x 12.7 cm NaI detector and the Tracor Northern PHA system. The PHA system has the capability of determining net peak areas.

The flux is calculated from:

$$J(\text{Ci}/\text{cm}^2\text{-sec}) = \frac{c\lambda^2}{\epsilon A(1-e^{-\lambda t_2}) (e^{-\lambda(t_3-t_2)} - e^{-\lambda(t_4-t_3)}) 3.7 \times 10^{10}} \quad (4)$$

where,

c = net observed counts

λ = radon decay constant (sec)

t_2 = time of exposure to radon flux (sec)

t_3 = time since start of exposure to start of count (sec)

t_4 = time since start of exposure to radon flux to end of counting interval (sec)

A = area of canister exposed to radon flux (cm^2)

ϵ = efficiency (counts/disintegration)

3.7×10^{10} converts disintegrations per second to curies

3.2.3 Canister Cross Calibration

To determine the detection efficiency of the counting system used for the project, several canisters were exposed to uranium mill tailings in test chambers for varying lengths of time and for different activity levels. The canisters were counted on the 12.7 x 12.7 cm NaI detector at least once before being shipped to the HASL for counting on their previously calibrated system. The canisters were then returned to Utah and counted several times subsequently.

The counting data are shown in Figure 3-4. An apparent radon half-life of 80 hr (instead of the expected 92 hr) is observed. This variation is probably due to radon redistribution within the charcoal in the canister and to leakage from the canister.

Based on the flux determinations provided by HASL, the detection efficiency for the 0.609 MeV gamma peak from Bi-214 was determined for each canister and is shown in Table 3-2. Efficiencies were determined using both the actual and the observed apparent half-life of radon in the canister. The 80-hr value narrowed the spread in observed efficiency. The efficiencies obtained from the first counts taken after exposure of the canisters (3 hr after exposure) minimize the differences. These values were averaged for use in the remaining measurements since most counting does take place shortly after exposure. Table 3-2 summarizes the pertinent data, including the HASL flux measurements.

3.2.4 Precision of Canister Data

Measurements have also been performed to check the precision of the canister measurements. Seventeen canisters were placed on a large area source within a 2-ft diameter. The canisters were exposed for 2 hr and counted after 3 hr to allow equilibrium to be established. The measurements yielded a flux of $1.65 \text{ fCi/cm}^2\text{-sec}$ with a standard deviation of $0.19 \text{ fCi/cm}^2\text{-sec}$. This deviation corresponds to 12% fluctuation in the flux values, assuming that the flux was actually constant over the large source. Allowing for other variations in counting and canister uptake yields a precision of about $\pm 15\%$ for all measurements.

FIGURE 3-1. LUCAS CELLS AND ALPHA PARTICLE COUNTING ELECTRONICS

FIGURE 3-2. SCHEMATIC OF DIRECT DEEMANATION SYSTEM

FIGURE 3-3. M-11 CHARCOAL CANISTERS AND BLOCK DIAGRAM OF ELECTRONIC COUNTING SYSTEM

FIGURE 3-4. CHARCOAL CANISTER CALIBRATION DATA

TABLE 3-1

EFFICIENCY OF LUCAS CELLS USED IN THIS STUDY

<u>Cell ID</u>	<u>Source</u>	<u>Efficiency</u>
1	1	0.83
2	1	0.83
3	1	0.83
4	1	0.83
5	1	0.83
6	1	0.83
7	1	0.83
8	1	0.83
A	2	0.64
B	2	0.23
C	2	0.66
D	2	0.66
E	2	0.47
F	2	0.67
G	2	0.46
H	2	0.43
I	2	0.57
J	2	0.62
F1	2	0.34
F2	2	0.31
F3	2	0.35
F4	2	0.40

<u>Source</u>
1. Rocky Mountain Scientific Glass Blowing Co.
2. FB&DU

TABLE 3-2

CANISTER CALIBRATION DATA

Canister and Count	Exposure Times		Count Times		Net Counts in 609keV Peak	Apparent Efficiency(%)		HASL Flux (fCi/cm ² ·s)
	Start	Stop	Start	Stop		92 hr Tl/2	80 hr Tl/2	
1-1	15:40	36:10	41:04	41:08	21624	3.25	2.88	12.9
1-2	15:40	36:10	60:07	60:11	17678	3.06	2.77	12.9
1-3	15:40	36:10	86:19	86:23	14553	3.08	2.87	12.9
1-4	15:40	36:10	107:35	107:39	12027	3.08	2.85	12.9
1-5*	15:40	36:10	132:15	132:25	14146	--	--	12.9
1-6	15:40	36:10	157:25	157:29	7828	2.83	2.85	12.9
1-7	15:40	36:10	178:37	178:41	5991	2.54	2.62	12.9
2-1	15:40	36:10	40:57	41:01	21527	3.41	3.02	12.2
2-2	15:40	36:10	60:14	60:18	17331	3.18	2.88	12.2
2-3	15:40	36:10	86:30	86:34	13426	3.00	2.80	12.2
2-4	15:40	36:10	107:17	107:21	11397	2.98	2.84	12.2
2-5*	15:40	36:10	132:00	132:10	13484	--	--	12.2
2-6	15:40	36:10	157:19	157:23	7718	2.94	2.75	12.2
2-7	15:40	36:10	178:31	178:35	6340	2.84	2.93	12.2
3-1	15:40	85:41	88:56	89:00	34466	3.01	2.73	7.64
3-2	15:40	85:41	107:11	107:15	28683	2.88	2.66	7.64
3-3*	15:40	85:41	131:40	107:50	33317	--	--	7.64
3-4	15:40	85:41	157:13	157:17	18548	2.71	2.66	7.64
3-5	15:40	85:41	178:24	178:28	15241	2.62	2.62	7.64
4-1	15:40	85:41	89:02	89:06	38639	2.79	2.53	9.25
4-2	15:40	85:41	107:29	107:33	33276	2.77	2.56	9.25
4-3*	15:40	85:41	131:20	131:30	39581	--	--	9.25
4-4	15:40	85:41	157:06	157:10	22358	2.70	2.64	9.25
4-5	15:40	85:41	178:18	178:22	18789	2.66	2.67	9.25
5-1	15:40	60:00	63:31	63:35	23983	3.29	2.94	7.05
5-2	15:40	60:00	86:44	86:48	18521	3.02	2.78	7.05
5-3	15:40	60:00	107:23	107:27	15323	2.92	2.75	7.05
5-4*	15:40	60:00	131:05	131:15	18136	--	--	7.05
5-5	15:40	60:00	156:43	156:47	8886	2.45	2.45	7.05
5-6	15:40	60:00	178:12	178:16	7656	2.50	2.54	7.05
6-1	15:40	60:00	64:01	64:05	31163	3.02	2.71	9.99
6-2	15:40	60:00	86:38	86:42	24388	2.80	2.58	9.99

TABLE 3-2 (Cont)

CANISTER CALIBRATION DATA

Canister and Count	Exposure Times		Count Times		Net Counts in 609keV Peak	Apparent Efficiency(%)		HASL Flux (fCi/cm ² ·s)
	Start	Stop	Start	Stop		92 hr Tl/2	80 hr Tl/2	
6-3	15:40	60:00	107:41	107:45	19795	2.67	2.51	9.99
6-4*	15:40	60:00	130:45	130:55	25426	--	--	9.99
6-5	15:40	60:00	156:11	156:14	12569	2.44	2.43	9.99
6-6	15:40	60:00	178:06	178:10	10437	2.39	2.44	9.99
7-1	15:40	105:35	108:35	108:39	29820	2.69	2.46	6.16
7-2*	15:40	105:35	130:30	130:40	37126	--	--	6.16
7-3	15:40	05:35	156:22	156:26	18756	2.42	2.34	6.16
7-4	15:40	105:35	177:44	177:54	39034	2.37	2.34	6.16
8-1	86:10	105:27	108:43	108:47	3406	3.27	2.89	2.11
8-2*	86:10	105:27	130:15	130:25	3722	--	--	2.11
8-3	86:10	105:27	155:21	155:31	4179	2.28	2.12	2.11
8-4	86:10	105:27	176:53	177:03	3243	2.08	1.99	2.11
9-1	86:14	105:24	108:49	108:53	578	2.95	2.60	0.40
9-2*	86:14	105:24	129:40	129:50	629	--	--	0.40
9-3	86:14	105:24	155:09	155:19	872	2.53	2.35	0.40
9-4	86:14	105:24	177:10	177:20	593	2.03	1.93	0.40
10-1	86:14	105:24	108:55	108:59	899	2.86	2.53	0.64
10-2*	86:14	105:24	130:00	130:10	1236	--	--	0.64
10-3	86:14	105:24	154:56	155:06	1553	2.80	2.61	0.64
10-4	86:14	105:24	177:26	177:36	1345	2.88	2.75	0.64

Average Efficiencies

Average of All Measurements

2.79±0.32

2.62±0.24

Average of 1st Count for Each Canister

3.05±0.24

2.73±0.20

* HASL Counts

CHAPTER 3 REFERENCES

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CHAPTER 4
DATA CORRELATION AND INTERPRETATION

CHAPTER 4

DATA CORRELATION AND INTERPRETATION

The theoretical considerations presented in this chapter are used to correlate and interpret the experimental data presented in Chapter 5. Specifically, general diffusion theory is used to evaluate the radon concentration and flux in bare and covered uranium mill tailings and to obtain effective diffusion coefficients. The analytical form of the diffusion coefficient is also examined to provide the functional dependence of the flux on absolute temperature and pressure.

4.1 Radon Soil Gas Concentrations Using a Finite Source

The radon gas concentration in bare tailings and in a tailing-cover material combination with a finite source can be modeled using diffusion theory. The main limitation of the theory is a result of assuming that the flux is proportional to the concentration gradient as given by Fick's law,

$$J(x) = \frac{D \, dC(x)}{dx} \quad (5)$$

where,

$J(x)$ = the radon flux ($\text{Ci}/\text{m}^2\text{-sec}$)

D = the effective diffusion coefficient (m^2/sec)

$\frac{dC(x)}{dx}$ = radon concentration gradient (Ci/m^4)

This limitation occurs because the flux is not necessarily proportional to the gradient of the concentration near or at interfaces and boundaries. At the boundary of the system the atmosphere acts as an infinite sink to radon gas. This limitation becomes apparent as the theoretical expressions for the flux are compared to experiment.

4.1.1 General Diffusion Equation

The general diffusion equation is derived from the steady-state equation of continuity where at a particular volume in tailings or cover the sources of radon (S') equal the sinks (the divergence of the flux and loss by decay).

$$\nabla \cdot \vec{J}(\vec{r}) + \lambda p C = S' \quad (6)$$

where,

$\nabla \cdot \vec{J}(\vec{r})$ = divergence of the flux (Ci/m³-sec)

p = porosity

C = radon concentration in soil gas (Ci/m³)

S' = radon source (Ci/m³-sec)

Using Fick's law and rearranging yields

$$\nabla^2 C - \alpha^2 C + S = 0 \quad (7)$$

where,

$$\alpha^2 = \frac{\lambda p}{D}$$

$$S = \frac{S'}{D}$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

The use of $D = k_o p$ for the effective diffusion coefficient, described by Culot et al., where k_o is the diffusion coefficient for air-filled space, accounts for the decreased diffusion area in a porous medium. (1)

The solutions of equation (7) for tailings material containing radon sources are:

$$C_t = Ee^{\alpha x} + Fe^{-\alpha x} + \frac{S}{\alpha^2} \quad (8)$$

In cover material containing no sources, solutions of the diffusion equation are given by:

$$C_c = Ge^{\alpha x} + He^{-\alpha x} \quad (9)$$

where the constants E, F, G, and H are determined by the boundary conditions.

(1) See end of chapter for references.

4.1.2 Boundary Conditions

The boundary conditions applicable to the experiments performed for this study are summarized in Table 4-1, and a schematic of the system is given in Figure 4-1. Only solutions in the x direction are considered here.

Using these boundary conditions and solving equations (8) and (9) for the integration constants, the equations describing the radon concentrations are:

$$C_t = C_o \frac{\cosh(\alpha x)}{\cosh(\alpha b)} + \frac{S}{\alpha^2} \left[1 - \cosh(\alpha(b-a)) \left(\frac{\cosh(\alpha x)}{\cosh(\alpha b)} \right) \right] \quad (10)$$

in tailings where C_o is the radon concentration at the top of the cover material, and

$$C_c = C_o \frac{\cosh(\alpha x)}{\cosh(\alpha b)} + \frac{S}{\alpha^2} \left[\cosh(\alpha(a-x)) - \cosh(\alpha(b-a)) \left(\frac{\cosh(\alpha x)}{\cosh(\alpha b)} \right) \right] \quad (11)$$

in cover material. In each equation the source term (S/α^2) is dominant except near the interface with air. All terms are defined in Table 4-1 and Figure 4-1 and "x" corresponds to some vertical position in the test chamber.

4.1.3 Source Modeling

The concentration C_o is a measured quantity while the source S is determined by using the relationship

$$S = \frac{R \rho \lambda E}{D} \quad (12)$$

as given by Culot et al.⁽²⁾ where the constants are emanating power E , density of tailings ρ , and ratio of grams of radium to grams of tailings R .

These parameters, given in Table 5-3, were determined experimentally.

4.2 Flux as a Function of Thickness of Bare Tailings

The flux across the surface of bare tailings can be evaluated using equation (5), with the concentration in tailings as given in equation (6). The thickness of the cover material is zero; therefore, $b = a$ and the flux from the tailings is given by:

$$J_t(a) = \frac{D_t}{\alpha} \tanh(\alpha a) [S - C_o \alpha^2] \quad (13)$$

The maximum flux, given in equation (14), is obtained when a increases to infinite.

$$J_t(\infty) = \frac{D_t}{\alpha} [S - C_o \alpha^2] \quad (14)$$

The ratio of the flux from tailings of a finite thickness to the infinite thickness flux is:

$$\frac{J_t(a)}{J_t(\infty)} = \tanh(\alpha a) \quad (15)$$

4.3 Flux as a Function of Cover Material Thickness

The flux as a function of cover material thickness is also evaluated using Fick's law and equation (11). The result is:

$$J_c(x) = -D_c \left[\frac{C_o \alpha \sinh(\alpha x)}{\cosh(\alpha b)} + \frac{S}{\alpha} (\sinh(\alpha(x-a)) - \cosh(\alpha(b-a)) \frac{\sinh(\alpha x)}{\cosh(\alpha b)}) \right] \quad (16)$$

Evaluating the flux at the surface of the cover material gives:

$$J_c(b) = \frac{D_c [S \sinh(\alpha a) - C_o \alpha^2 \sinh(\alpha b)]}{\alpha \cosh(\alpha b)} \quad (17)$$

4.4 Theoretical Dependence of the Flux on Absolute Temperature and Pressure

From Fick's law, the flux is directly dependent on the diffusion constant and the concentration gradient (which itself is dependent upon the diffusion coefficient, porosity, and emanating power). Although the flux is the product of the diffusion coefficient and the gradient of the concentration, the absolute temperature and pressure dependence of the flux can be shown to be most directly attributable to the diffusion coefficient. Two theoretical formulations for the diffusion coefficient are based upon the diffusion of binary gas mixtures and "Knudsen" diffusion.

4.4.1 Binary Gas Diffusion

If the pores are large in relation to the mean free path of the diffusing particles and there is no surface diffusion, the dominant diffusion process is that of ordinary molecular diffusion within the medium contained in the pores. The diffusion coefficient for binary gas diffusion is proportional to the 3/2 power of the absolute temperature and inversely proportional to the absolute pressure. (3)

$$D_B \propto \frac{T^{3/2}}{P} \quad (18)$$

4.4.2 Knudsen Diffusion Theory

Knudsen diffusion is encountered if the pore size is small in relation to the mean free path or if the pressure is low. (3) The diffusion particles then collide more frequently with the wall than with other particles in the porous volume. The diffusion constant for this type of diffusion is proportional to the square root of the absolute temperature and has no pressure dependence. (3)

$$D_K \propto T^{1/2} \quad (19)$$

Culot et al. (1) have analyzed the diffusion of radon gas through concrete using Knudsen's theory for an explanation of corrections to the diffusion coefficient. The applicability of Knudsen's theory is attributed to the low porosity of concrete.

FIGURE 4-1. SCHEMATIC REPRESENTATION OF RADON SOURCE AND COVER MATERIAL

TABLE 4-1

BOUNDARY CONDITIONS FOR DIFFUSION EQUATION

-
-
(1)	$J_t(o) = 0$	flux is zero at the bottom of the test chamber
(2)	$C_t(a) = C_c(a)$	concentration is continuous across interface of tailings and cover material
(3)	$J_t(a) = J_c(a)$	flux is continuous across the tailings-cover material interface
(4)	$C_c(b) = C_o$	the concentration must equal the experimentally determined concentration at the top of the cover material
-
-

CHAPTER 4 REFERENCES

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CHAPTER 5
EXPERIMENTAL RESULTS

CHAPTER 5

EXPERIMENTAL RESULTS

This chapter describes the experiments that were performed and the data that were obtained. Correlation and interpretation of the data using equations given in the previous chapter are also presented.

5.1 EMANATING POWER OF URANIUM MILL TAILINGS

The emanating power of radon has been studied to parameterize models to predict radon exhalation from tailings. Emanating power is defined as that fraction of radon produced in some mineral matrix which escapes the matrix and is free to diffuse in the pore spaces. Values of the emanating power of uranium ores range from 1% to 91% and show that the emanating power is dependent on many parameters such as porosity, particle size, mineral species, radium mineralogy, etc.⁽¹⁾ Emanating powers of approximately 20% have been used to model radon sources from western sites.⁽²⁾

For this study, the emanating powers of uranium mill tailings from the Vitro site have been measured for composite and size-separated samples. A composite emanating power was also reconstructed from the emanating power of the size-separated samples. The uranium mill tailings were also leached with hydrochloric acid, and the emanating power was remeasured in order to ascertain some properties of the emanating source.

5.1.1 Emanating Power of Composite Uranium Tailings

The principal method used to determine the emanating power is described by Scott et al.⁽³⁾ Dry uranium mill tailings were deemanated to free the radon gas by a series of dry screenings. The screenings produced no size separations and samples were otherwise untreated in any respect. The tailings were then sealed in cans to trap all radon that emanates from the material. After allowing equilibrium of the radon daughters to be established, the can of tailings was analyzed using a NaI detector and a pulse height analyzer, as described in paragraph 3.3, to determine the initial activity A_0 of ^{214}Bi and hence the activity of the residual radon trapped in the crystalline structure of the minerals after deemanation. Waiting 30 days allows the radon to grow back into complete equilibrium with its radium progenitor. The additional amount of radon A_1 is equal to the amount that had been removed previously from the tailings by deemanation. The percent emanating power of the uranium tailings is then given by:

(1) See end of chapter for references.

$$\% \text{ emanation} = 100 \times \left[1 - \frac{A_0}{A_\infty} \right] \quad (20)$$

where,

A_0 = initial activity

A_1 = radon activity deemanated

$A_\infty = A_1 + A_0$ the activity after 30 days

A modification of this procedure was also used to avoid the 30-day wait. The activity was determined at several times after deemanation and the resulting data were fit by the method of least squares to the equation:

$$\text{Activity} = A_0 + A_1 (1 - e^{\lambda t}) \quad (21)$$

to determine the parameters A_0 and A_1 . Using these best fit parameters gives:

$$A_\infty = A_0 + A_1 \quad (22)$$

and the emanating powers can be determined.

To determine the emanating power of the gross composite uranium mill tailings, 10 different samples were deemanated and processed as described above. Table 5-1 lists the observed values of emanating power. The average emanating power is $20.2 \pm 1.5\%$, a value consistent with other discussions of the emanating power of western uranium mill tailings. (2)

5.1.2 Emanating Power as a Function of Particle Size

The emanating power and particle size fraction distribution of six different size groups are presented in Table 5-2. These emanating powers were obtained exactly as in paragraph 5.1.1, except the dry sample was screened according to size. Multiplying the measured emanating power of each size fraction by its mass fraction and summing over the different fractions, yields a composite emanating power of 18.1%. The difference between the summed fractions and the gross composite is 2.1%, a value within the uncertainties associated with the measurements. With the exception of the largest size fraction group, the emanating power is relatively constant and independent of size ranging from 16 to 19 which is probably within the experimental error.

5.1.3 Effects of Leaching on Emanating Power

The effects of HCl acid leaching on the emanating power of coarse, unsized Vitro tailings were examined to determine the nature of the radium deposition in the tailings. The laboratory method involved taking a sample of coarse Vitro tailings and

determining its emanating power. The tailings were then leached with 12 molar HCl acid for 48 hr and washed with water for 12 min. The tailings were then dried and the emanating power remeasured. The radon emanating power from the residual radium in the sample increased by a factor of 2. A check of the leachate indicated that only a minor fraction of the radium in the sample was removed. Apparently leaching may be dissolving the outer mineralization to expose new surfaces on both coarse sand grains and on the fine particles.

5.2 RADON SOIL-GAS CONCENTRATION

Experimental measurements of the radon gas concentration profile in sand and dry bentonite over tailings have been performed to assess the effectiveness of earth cover materials in reducing the radon surface flux. Experimentally determined parameters were used in the theoretical model for radon concentration developed in paragraph 4.1. Good agreement was obtained with model predictions and experimental measurements of radon concentration.

The experimental configurations consisted of placing tailings in two 55-gal test chambers to a depth of 2 ft. Gas sampling was accomplished with 25 mil ID stainless steel tubing which extended through the chamber walls. A medium fritted glass filter on the tubing prevented fine tailings particles from entering the tubing. For the radon concentration measurements, an evacuated Lucas cell was attached to the sampling tube and soil gas was withdrawn from the interior via the steel tubing and an additional filter to remove radon daughters. The cell was counted as described in paragraph 3.1 to determine the radon concentration in the extracted soil gas. All penetrations into the drum were sealed with epoxy and the tubing ends capped when samples were not being taken to prevent radon loss through the tubing and holes in the drum.

The test chamber containing sand as a cover material was 12-ft high, accomodating 2 ft of tailings and up to 10 ft of sand. The test chamber containing the dry bentonite was 6-ft high with 2 ft of tailings and up to 3.5 ft of bentonite. Figure 4-1, Chapter 4, gives a schematic representation of the system.

Figures 5-1 and 5-2 show the experimentally and theoretically determined radon gas concentrations in sand and bentonite cover material. Equations (11), (12), and (13) were used to correlate the data. The parameters for the source term were determined and are summarized in Table 5-3. The porosities of sand and tailings were measured to be 0.30 and 0.28, respectively, and were assumed to be equal in all calculations. The diffusion coefficient for uranium tailings has been measured by many authors and ranges from 9×10^{-3} cm²/sec to 5×10^{-2} cm²/sec. Matching the experimental data with diffusion theory predictions gave an effective diffusion coefficient of 3×10^{-2} cm²/sec for both tailings and

cover material. The radon gas concentration was measured at the interface of the cover material and air and was used as a boundary condition. Using these parameters, the radon gas concentration was very effectively modeled using diffusion theory.

The above experiments and analysis demonstrate the applicability of diffusion theory in modeling radon gas concentrations. Its further utility can be seen by the relatively small amount of information needed to model the radon source.

5.3 SURFACE RADON FLUX AS A FUNCTION OF BARE URANIUM TAILINGS DEPTH

The surface radon flux as a function of uranium tailings depth was also investigated and compared to the semi-empirical curve given by Schiager.⁽²⁾

The radon flux was measured using the charcoal canister technique for varying depths of coarse sandy and 200 mesh fine uranium tailings and corrected for pressure variations. The results plotted in Figure 5-3 were fit to Equation (13) using an iterative least squares routine to determine the infinite flux and the effective diffusion coefficient. The flux values normalized to the infinite flux are plotted in Figure 5-4 and show that the flux for these tailings reach saturation at a depth of 25 to 50% greater than predicted by Schiager.⁽²⁾

The curves are described by Equation (14) and the differences are due to variations in the effective diffusion coefficient D . Physically, these differences in flux can be attributed to variations in the porosity to which the effective diffusion coefficient is related. The effective diffusion coefficient may, therefore, be readily deduced from the flux attenuation as a function of depth of tailings.

5.4 THE EFFECTS OF COVER MATERIAL ON RADON EXHALATION

As can be seen from Figure 5-5, the theoretical prediction for the surface flux using experimentally determined modeling parameters is about a factor of 2 greater than the experimental measurements of the flux through a sand cover. Determination of the source of the difference would require further examination. Also, the difficulty of making accurate measurements of C_0 at the soil-air interface can introduce uncertainties in the theoretical flux curve.

The theoretical functional dependence is essentially exponential at a distance of 6 ft or more from the radon source and gives a relaxation length of 2.5 to 3.0 m. This value of relaxation length is in disagreement with the experimental data and is higher than the value reported by Schiager.⁽²⁾ Assuming the flux is exponential beyond 6 ft and fitting the apparent slope of the data, a relaxation length of 1.4 m is observed,⁽²⁾ which is in good agreement with the value report by Schiager.⁽²⁾ Because

of the uncertainties, a range could be assigned to the relaxation length from 1.3 to 1.7 m. Except for the absolute magnitude of the flux, the model gives a fair approximation to flux behavior and some adjustment of the parameters in a phenomenological approach may provide a better fit of the data.

5.5 MEASURED EFFECTS OF ABSOLUTE TEMPERATURE AND PRESSURE ON RADON FLUX

The diurnal variation of radon concentration has been observed and reported by many authors.^(4,5,6) Of these, only Kovach⁽⁶⁾ has performed correlations with temperature. Because of the way in which these experiments were performed, other variables such as pressure, wind, and temperature could not be controlled. The experiments in the present study were performed in the laboratory to facilitate some control over atmospheric variables.

The absolute temperature and pressure dependence of the radon flux was investigated and the results were compared with the two expressions given in paragraph 4.4. These two proportionality expressions represent extremes in the pressure dependence of the flux, while the temperature variation is more subtle. The results indicate the radon gas diffuses as a binary gas system although over the range of normal temperatures and pressures, the change in magnitude of radon flux is small and on the order of 10% or less for either.

Pressure measurements were performed at constant temperature in a steel pressure vessel approximately 1 ft in diameter and 3 ft in length. A cylindrical radon source of uranium mill tailing, 10 in. in dia by 10 in. in height, was placed within the vessel, and the flux was measured at atmospheric pressure. All flux measurements were made using the charcoal canister techniques described in paragraph 3.2, Chapter 3. The flux measurements for pressure less than atmospheric were made by evacuating the pressure chamber with the tailings inside and allowing the system to come to equilibrium. The vacuum was then released, a charcoal canister placed on the tailings, the vacuum reestablished and the flux measured. The premeasurement evacuation served to condition the tailings and remove excess radon if present. For pressures greater than atmospheric, the same procedure was followed except the system was pressurized with aged air.

The absolute pressure dependence is plotted in Figure 5-6. The theoretical curve corresponds to the $1/P$ pressure dependence of a binary gas system. Assuming the $1/P$ absolute pressure dependence for the flux, the change in flux for a change in pressure from 14 to 15.5 psia is 10%. This small change would be comparable to the accuracy of the measurement-technique used and may not be discernible over these small pressure differences.

The temperature measurements were performed at atmospheric pressure using a refrigerator and oven to vary temperature. The

tailings were allowed to reach equilibrium at a specified temperature and the flux was then measured. The experimental data are presented in Figure 5-7 and show the $T^{3/2}$ and $T^{1/2}$ flux dependence as predicted in paragraph 4.4, Chapter 4. The variation of flux with temperature over the range indicated is not as discernable as the pressure dependence, but the $T^{3/2}$ temperature dependence provides a better fit to the data.

Because the gradient of the partial pressure is proportional to the gradient of the concentration, the dependence of the flux on pressure and temperature can be expressed by the following form of Fick's law:

$$J \propto \frac{T^{3/2}}{P} \nabla P \quad (23)$$

Considering the normal ranges of pressure and temperature, the maximum absolute change in flux for the normal ranges of atmospheric pressure is about 10% and for normal temperature ranges it is about 20%. However, rapid changes in pressure can give rise to significant transients in the radon flux.

5.6 EFFECTS OF MOISTURE IN TAILINGS ON SURFACE RADON FLUX

To determine the effects of moisture changes on surface radon fluxes, water was added and allowed to evaporate from test chambers containing coarse (sandy) Vitro tailings. The fluxes were determined simultaneously using both the charcoal canister and the Lucas cell/accumulator drum methods. Fluxes were determined at a given tailings moisture content, and water added or allowed to evaporate before remeasuring the fluxes. The tailings moisture content was varied in weight percent increment from dry (0%) to saturated (~20%) by adding water, and then back to dry by evaporation. The cycle was repeated to check the results.

Table 5-4 lists the data obtained for simultaneous measurements of radon surface fluxes over a period of about 6 days for dry tailings and tailings with 15 weight percent water added at the start of the experiment, but allowed to dry by evaporation during the 6 days. The wet-to-dry flux ratios show the effect on the fluxes as the moisture evaporates.

Table 5-5 lists the results of a series of measurements for tailings taken at the indicated moisture content. The tailings were saturated at about 20 weight percent water. Figure 5-8 illustrates the general behavior observed for a few cycles from dry to saturated and back to dry from the Lucas cell data.

From these data it can be seen that both moisture content and the rate of evaporation appear to be important in the degree of radon attenuation observed for adding water to tailings. When adding water to increase the moisture content, measurements were begun within hours after addition of the water. When drying out, measurements were taken over a period of days after the last addition of water.

From Table 5-5 it may be seen that the Lucas cell/accumulation drum method and the charcoal canister techniques show different responses to the moisture changes. The charcoal canister measurements showed more variability in response. This could be caused by absorption of water on the charcoal with an attendant reduction in effectiveness for attaching radon. Qualitatively similar results have been reported elsewhere^(7,8) for radon fluxes and moisture content, although the common conception is that adding moisture reduces the radon flux. Further evaluation and study of these effects are required to obtain a more definitive understanding of the relationships between moisture and fluxes.

5.7 EFFECT OF WINDSPEED ON RADON SURFACE FLUXES

A small wind chamber was constructed as shown in Figure 5-9 to examine the effects of windspeed on surface fluxes. The small size was chosen so that the windspeeds obtained occurred uniformly over the tailings surface. A 5-gal container of tailings was used for the tests conducted. A vacuum pump pulled air through the apparatus across the tailings surface through a flow-through HASL-type radon flask coated with ZnS phosphor. After the "wind" had blown steadily across the tailings for a few minutes, the flask valves were closed and the entrapped sample analyzed for radon content. The concentration of radon in the flask under these steady state conditions is related to the surface flux from the tailings by the following relationship:

$$\phi = C \times W \times \frac{A_C}{A_S} \quad (24)$$

where,

$$\phi = \text{surface flux in } \frac{\text{Ci}}{\text{cm}^2\text{-sec}}$$

$$C = \text{concentration in the radon flask in Ci/cm}^3$$

$$W = \text{windspeed in cm/sec}$$

$$A_C = \text{cross sectional area of the wind chamber in cm}^2$$

$$A_S = \text{surface area for radon exhalation in cm}^2$$

The windspeed was determined from the volumetric flow rate of air through the system and area of the wind chamber. Concentrations of radon in the air were obtained by counting the HASL flask using the 12.7-cm dia photomultiplier tube.

It was observed that the volumetric flow rate of air through the system was not a constant. More air exited the wind chamber than entered through the inlet port. The difference was made up of tailings soil gas pulled into the apparatus by the suction from the vacuum pump. To increase the resistance to flow through

the tailings 2 cm wide, vertical flanges were added around the base of the wind chamber. The flanges were forced into the tailings surface to eliminate the leakage of air between the base of the wind chamber and the tailings.

In an attempt to quantify the effects of having the tailings soil gas enter the system by vacuum suction instead of by the Bernoulli-type pressure drop caused by the wind itself, the inlet to the wind chamber was blocked in a series of tests, resulting in fluxes due to soil gas removal alone. These data were used to correct for the differences in volumetric flow rates.

The following table and graphs summarize the data obtained. Table 5-6 lists the pump and inlet volumetric flow rates, calculated windspeeds, measured radon concentrations in the HASL flasks, and resultant surface fluxes for the flanged cases. Figure 5-10 shows the effect on vacuum losses from adding the vertical flanges to the wind chamber. Figure 5-11 shows the net surface flux variations as a function of windspeed over the tailings, corrected for the vacuum effect.

The windspeeds used in these experiments represent a lower limit to determine radon flux variations. For small windspeeds where essentially laminar flow exists near the surface of the earth, the velocity profile is parabolic with zero windspeed at the surface of the earth.⁽⁹⁾ Higher windspeeds develop turbulent flow with a nonuniform velocity profile which could pick up dust. The wind chamber thickness was small; therefore, low wind velocities were used to approximate laminar flow and to avoid dust loading of the sample gas passing over the tailings.

In general, it appears that the surface fluxes are increased as the windspeed increases. Actual in situ effects will be difficult to quantify because of the irregularities in surface contours and large variations in windspeeds with time and nearness to the surface. These experiments do show, however, that there is a net effect expected that may be relatively large.

5.8 THE EFFECT OF CHEMICAL STABILIZERS ON RADON SURFACE FLUXES

A series of measurements were performed using Vitro tailings samples and various chemical treatments in order to determine the radon flux attenuating properties of the chemicals. Chemical stabilization techniques can be classified as either surface or volumetric, depending on whether the stabilizing agent is applied to the surface or is mixed into the tailings matrix. Both types were evaluated in this program.

Basically, tailings samples were prepared in small containers and radon surface fluxes measured using the charcoal canister technique. The chemical stabilizer was then applied (reserving at least one untreated sample as a control) and the surface fluxes were remeasured at periodic intervals. The effectiveness of the stabilizer in reducing radon surface flux is reported as percent radon flux reduction or $100(1 - \phi_{\text{treated}} / \phi_{\text{untreated}})$.

5.8.1 Surface Stabilizers

The surface stabilizers tested included epoxy mixtures, asphaltic emulsions, plastic foams, and other organic materials applied by pouring to the tailings surface. Table 5-7 lists the surface stabilizers tested under laboratory conditions and indicates the effectiveness in inhibiting radon exhalation from the tailings. Table 5-8 shows the results of a test plot at the Vitro site.

A small quantity of Armak E-63 asphaltic emulsion was obtained from Battelle Pacific Northwest Laboratories and applied to a tailings sample to provide a comparison of the methods used for determining the effectiveness of surface stabilization. A film of asphaltic emulsion approximately 1/8-in. thick was applied and allowed to dry. A second application was added to the top to obtain a total emulsion thickness of about 1/4 in. After the emulsion had dried for a few days so that it was no longer too sticky, a canister was sealed to the surface of the emulsion. A second canister was placed at the same time on the untreated control sample of tailings. After exposure, the canisters were counted and the radon exhalation flux reduction was determined to be 95% compared to untreated tailings.

Battelle reports that radon permeation through a 1/8-in. thick E-63 asphaltic emulsion seal was not measurable with their apparatus.⁽¹⁰⁾ The results obtained by FB&DU indicate approximately two orders of magnitude reduction in flux, but show there appears to be a finite permeation of radon through the asphaltic emulsion.

Tests have also been conducted with the sulfur compound developed by the Bureau of Mines in Boulder City, Nevada. This material was demonstrated as being very effective in radon control, reducing the flux to 7% of its uncovered value.⁽¹¹⁾ In the present tests, the radon flux from the covered and uncovered tailings plots at Boulder City were measured with the charcoal canister technique during a 2-hr period in October, 1976. During these measurements, fluxes were determined on covered and uncovered tailings, and on uncovered tailings in which the stabilizing material had a hairline crack. In these measurements, the covered flux was 58% of the uncovered value. Furthermore, the flux through the cover with a crack in it was 92% of the uncovered value. These results indicate significant degradation of the radon attenuating properties of this material in a period of about 2 yr.

5.8.2 Volumetric Stabilizers

5.8.2.1 Chemfix

The volumetric stabilizers tested were Chemfix, prepared by Delaware Custom Materials, and Calcilox, prepared by Dravo Corp.

Mr. Rodger Gradlund of Delaware Custom Materials prepared samples of Vitro tailings stabilized with cement and silicate mixtures (Chemfix) for testing.

The tailings samples available were of two types: a sandy granular material, and a fine gray clay-like material. The sandy tailings had small lumps of the clay-type material dispersed in it. Both types of samples had been dried. The cement used was a type 2 Portland cement and the silicate solution had a specific gravity of 1.4 g/ml. For the purpose of calculating volumes of mixed samples, the density of sandy tailings was determined to be 2.5 g/ml, for the fine tailings it was 2.32 g/ml, and for cement 3.03 g/ml.

After testing a number of smaller samples to obtain desirable mixing ratios, a set of three samples using larger quantities of materials were prepared and placed in 5-gal steel pails (6-gal pail for sample 1067). Sample 1067 was a stabilized mixture identical to sample 1066 poured over 7.2 kg of dry tailings. Some of the liquid from the stabilized tailings mixture seeped into the dry tailings, causing some settling and bubbling of the displaced air up through the cement-silicate mixture. This sample was prepared to determine whether the stabilized tailings would act as a barrier to radon originating in underlying untreated tailings. Control samples with the same weight of dry, sandy and fine tailings were also prepared in 5-gal pails. The composition of the samples is given in Table 5-9.

An additional set of samples was prepared using 4 kg of dry, screened sandy tailings in 3-gal metal pails after evaluating the preliminary results from earlier samples. In these samples, the tailings were covered with mortar or stabilized cement containing no tailings to determine the amount of radon diffusion through the material. A control sample of the same weights of dry tailings was also prepared. These samples are also described in Table 5-9.

Samples 1092 through 1096 indicate the resistance of clean, very hard and medium hard cement silicate to radon diffusion in comparison with unstabilized concrete. The effect of water on the underlying tailings and/or the effect of bubbles in the material can also be checked with this set of samples.

The first radon emanation rate measurements taken showed that the treated samples had higher emanation rates from the surface than the untreated dry tailings. This phenomenon has been observed before with the addition of water to tailings. However, after 3 days the treated samples showed rates slightly less than the controls. Measurements over a long period of time will be needed to determine the actual reduction in radon emanation from the stabilized tailings. Table 5-10 shows the apparent exhalation reduction for the samples described. The exhalation reduction ranges between 0 and 90% for measurements taken one week after stabilization. The long-term effectiveness of Chemfix stabilization has not been determined.

5.8.2.2 Calcilox

Laboratory tests were performed at the Dravo Corporation, New Technology Development Laboratory, to determine the feasibility of stabilizing uranium mill tailings with Calcilox* additive. Tailings from the abandoned Vitro plant were obtained by FB&DU and sent to Dravo for testing.

Calcilox stabilization techniques have previously been employed to stabilize SO₂ scrubber sludges and fine refuse slurries from coal preparation. In these cases, the Calcilox additive acts to chemically "fix" the solid particles, and consequently, encapsulate the pore fluid. This fixation results in an increase in shear strength, decrease in permeability, decrease in compressibility, decrease in erodibility, and generally creates a more environmentally acceptable material.

Laboratory tests were designed to study the following Calcilox stabilization techniques:

- (a) Determine the acceptable mixture ratios for Calcilox additives in the tailings.
- (b) Determine the necessity for pretreating the tailings before adding the Calcilox additive and for modifications to the Calcilox additive.
- (c) Determine the effects of other variables to be encountered in an eventual system design to stabilize the full tailings mass such as moisture content, pH, temperature, etc.
- (d) Measurement of the radon exhalation reduction from samples of stabilized tailings and effluents.

The tailings had a moisture content of 5 to 10%. Most of the particles were sand-sized as indicated by dry screen analysis. Wet screen analysis, however, resulted in more fines (18% passing the No. 200 sieve for the wet analysis, only 7% passing the No. 200 sieve for the dry analysis). This indicates that the fines are cemented together to some extent.

Acidity tests were performed by adding small amounts of hydrated lime to a 40% solids tailings slurry and noting the pH. Approximately 0.4 to 0.5% hydrated lime was required to adjust the pH to 11.0, based on the weight of tailings solids. Generally, the Calcilox process requires a pH of 11.0 to 11.5 for optimum stabilization rates, and for this reason, lime additions of 0.5 and 1.0% were used in the testing program.

It is concluded that a 5% Calcilox additive, 1% hydrated lime addition will stabilize the uranium tailings with an imper-

*Calcilox is a registered trademark of Dravo Corporation.

vious surface and should substantially improve the material's engineering properties. This in turn should remedy dusting problems due to the increase in cohesion between the tailings solids. A 7-1/2 to 10% Calcilox addition reduced the permeability of the tailings by a factor of at least 5 to 10. Consequently, Calcilox stabilization techniques should reduce the flow rate of contaminated water from the tailings by a considerable amount. It was decided, based on the results of penetration and permeability tests, that 5 and 7.5% Calcilox additions be tested at solid contents of 40 and 87%. Table 5-11 lists the radon exhalation reduction test samples.

Enough tailings were treated to fill a 1-gal paint can with a 3-in.-thick layer of treated tailings. Duplicate samples were made for all tests. Samples of -50 mesh, +50 mesh, and the composite tailings sample were tested to establish the effect of particle size. After 15 days of curing at 70° F the supernatant water was removed from the 40% solid content samples, prior to exhalation flux measurements.

The results of the radon exhalation reduction tests of Calcilox-treated tailings are presented in Table 5-12. Exhalation reduction ranges from 98 to 10%, showing that there is some attenuation of the flux associated with Calcilox stabilization in the short-term time frame of this experiment. The treated tailings arrived in Salt Lake City in a broken and fractured condition, they were presumably disturbed by the transport from Pennsylvania to Utah. The fractured condition of the treated samples could have significantly decreased the radon exhalation factors over those expected from more normally cured cases.

5.9 GAMMA-RAY BUILDUP IN COVER MATERIAL

Several experiments have been performed to determine the decrease in gamma radiation alternatives due to gamma-ray buildup in tailings cover resulting from radon diffusion through the cover. As the radon decays, daughters could precipitate in the cover material and produce a source of gamma rays. This potential buildup could cause additional radiation shielding problems that would need to be considered in a tailings stabilization program.

To investigate the potential buildup program, seven cylindrical containers with a 10 in. diameter were filled with 1 ft of uranium mill tailings. Three containers were sealed so that radon could not diffuse through the top surface. One sealed container and one unsealed container each had 1 ft of sand cover material placed over it. Similarly, additional sealed and unsealed containers had 2 and 3 ft of sand cover material placed over them. The containers were left undisturbed for 6 weeks to allow the radon diffusion and radon daughter buildup in the unsealed containers to reach an equilibrium condition.

Previously, good geometry experiments with a point source of ^{137}Cs gamma rays verified the gamma-ray attenuation coeffi-

cient of the sand cover material for 0.6 MeV gamma-rays to be 1.1 mm^{-1} .

The experimental arrangement for the gamma counting consisted of placing a collimated, well shielded, 7.6 x 7.6 cm NaI detector 4 ft from the floor and locating the tailings and cover material under the detector. The tailings-to-detector distance was constant at 3 ft. The distance between the top of the cover material and detector were 2, 1, and 0 ft, depending on the amount of cover material present.

The gamma-ray spectrum was obtained and analyzed to determine the net counts in the 0.609 MeV gamma-ray peak of ^{214}Bi . The positive difference in net counts obtained between the cover material in which radon diffusion was allowed and the cover material of the same thickness in which no diffusion was allowed is attributed to the gamma-ray buildup in the cover material. Table 5-13 shows the counts obtained in the 0.609 MeV peak for various sand cover thicknesses over tailings with and without radon gas diffusion in the sand. As seen in the table, there was no statistically valid gamma-ray buildup for various cover material depths observed. The small changes in net counts in the 0.609 MeV peak could be associated with changes in the background radon content of the room air, and indicate that whether or not the radon from the tailings is allowed to diffuse through the cover material, the gamma-ray attenuation is basically the same.

Other measurements were performed to detect buildup of the 0.609 MeV peak in sand cover at a point 2.89 m above the large radon source as described in Figure 4-1, Chapter 4. These results were negative and showed no buildup of ^{214}Bi in the cover material at that height. All these results indicate that gamma-ray buildup is small, and is less than 10% for cover material depths investigated.

5.10 VEGETATIVE STABILIZATION

A series of experiments were performed to investigate the feasibility and effects of the growth of vegetation in tailings and in soil cover material over tailings. Vegetative covers have been investigated in the past(12-14) for suitability in tailings stabilization, but relatively little is known about the effects of root penetration through cover materials and of plants growing in tailings. Most of the effort for this task was subcontracted to Dr. L. H. Wullstein, Professor of Biology at the University of Utah. Dr. Wullstein's report is included as Appendix A.

The vegetative stabilization experiments included field and laboratory tests to determine the effects of tailings on the growth of certain selected grasses. In the field experiments conducted by Dr. Wullstein, five plots of ground were prepared for planting, four with different fertilizers and one as a control plot. Each plot was planted with 12 rows of grasses, each row being a different species of grass. One additional area

without fertilizer treatment was planted with hybrid species of Cynadon and Paspalum grasses.

In all subplots all grasses seeded, germinated profusely, and survived as long as the water treatments continued. The hybrid plantings (whole plants) continue to grow and are expected to survive the summer weather. The toughest test for these hybrids will be winter survival since their parent plants naturally evolved under an exceeding hot climate but mild winter.

There seems to be little doubt that the seeded species would continue their growth provided optimum moisture is available. No evidence of marked or critical toxicity symptoms were noticed; however, these symptoms may appear with longer growth.

Additional field studies showed that an annual grass (barnyard grass) already growing at the Vitro site could be seeded and grown on bare tailings with no plot preparation or watering. The plants grown this way (Figure 5-12) are also forming new seed and starting to spread.

The laboratory experiments consisted of growing three sets of plants of Cynadon dactylon and three sets of Paspalum vaginatum in tailings with 12 in. of cover soil and three sets of plants each in tailings without soil cover. As shown in Figure 5-13 (Photos 1 through 4), roots of each plant penetrated into the tailings and were undepleted. Plants in bare tailings showed similar signs of good growth although it was noted that equivalent growth of the roots took a longer period of time in the tailings.

The experiments show that many grasses will grow in uranium mill tailings, especially Paspalum vaginatum, Cynadon dactylon and the barnyard grasses growing at the Vitro site. Roots penetrate undeflected and show no "matting" at the soil cover-tailings interface. Because of the root penetration, preferential channels of radon escape may be formed.

FIGURE 5-1. RADON CONCENTRATION IN TAILINGS AND COVER MATERIAL (SAND)

FIGURE 5-2. RADON CONCENTRATION IN TAILINGS AND COVER MATERIAL (BENTONITE)

FIGURE 5-3. RADON FLUX AS A FUNCTION OF TAILINGS DEPTH

FIGURE 5-4. NORMALIZED RADON FLUX AS A FUNCTION OF TAILINGS DEPTH

FIGURE 5-5 SURFACE RADON FLUX AS A FUNCTION OF COVER MATERIAL THICKNESS

FIGURE 5-6. ABSOLUTE PRESSURE DEPENDENCE OF THE RADON FLUX

FIGURE 5-7. ABSOLUTE TEMPERATURE DEPENDENCE OF THE RADON FLUX

FIGURE 5-8. EFFECT OF MOISTURE ON RADON FLUX

FIGURE 5-9. SCHEMATIC OF WIND CHAMBER

FIGURE 5-10. WINDSPEED BASED ON INLET VOLUME FLOW RATE VERSUS WINDSPEED BASED ON PUMP VOLUME FLOW RATE

FIGURE 5-11. WINDSPEED EFFECT ON SURFACE RADON FLUX (CORRECTED FOR VACUUM EFFECT)

General View of Barnyard Grass

Individual Plant of Barnyard Grass

Figure 5-12. Barnyard Grasses

Photo 1. Paspalum

Photo 2. Cynadon

Photo 3. Cynadon

Photo 4. Paspalum

Figure 5-13. Root Growth in Tailings

TABLE 5-1

EMANATING POWER OF COMPOSITE URANIUM MILL TAILINGS

Sample ID	Mass (g)	A_0	A_∞	% Emanating Power
C1	296	5.34×10^5	6.42×10^5	16.7
C2	297	4.62	5.73	19.3
C3	288	4.64	5.86	26.7
C4	281	4.58	5.68	19.5
C5	297	4.57	5.72	20.1
S1	25	5.68×10^4	7.34×10^4	22.5
S2	24	5.86	7.42	21.1
S3	23	5.69	7.18	20.8
S4	24	5.87	7.34	20.0
S5	23	5.46	6.92	21.1

Average emanating power = $20.2 \pm 1.5\%$

TABLE 5-2

EMANATING POWER OF URANIUM MILL TAILINGS AS A FUNCTION OF SIZE

Sample ID	Particle Size mm	Tyler Scale	Size Fraction Weight Percent	% Emanating Power
AA	>1	16	8	23.1
BB	0.5 to 1	32	7	16.0
CC	0.25 to 0.5	60	19	16.6
DD	0.125 to 0.25	115	36	17.1
EE	0.075 to 0.125	200	25	18.9
FF	0 to .075	200	6	17.5

TABLE 5-3
SUMMARY OF CONSTANTS USED

p (porosity)	0.3
E (emanating power)	0.2
D (effective diffusion coefficient) . .	$3.0 \times 10^{-2} \text{ cm}^2/\text{sec}$
λ (radon decay constant)	$2.097 \times 10^{-6} \text{ sec}^{-1}$
R (ratio: radium to tailings)	$0.78 \times 10^{-9} \text{ gRa/g}$ tailings
ρ (density of tailings)	1.6 g/cm^3

TABLE 5-4

FLUX VERSUS TIME FOR WET AND DRY TAILINGS

Starting Time for Canister Exposure (hr)	Flux (10^{-15} Ci/cm ² -sec)		Flux Ratio <u>Wet</u> Dry
	Initial Moisture 15%	Tailings Dry	
14	1.26	1.64	0.77
18	1.33	1.83	0.73
21	0.59	0.36	1.64
44	1.32	0.48	2.75
82	1.37	0.99	1.38
114	1.49	1.12	1.33
140	1.52	1.53	0.99

TABLE 5-5

RADON FLUXES VERSUS TAILINGS MOISTURE CONTENT

Case	Measurement Type	Moisture Content (wt %)	Normalized Flux (ϕ / ϕ dry)
1	Canister	Dry	1.00
2	Canister	15	0.69
3	Canister	Dry	1.00
4	Canister	5	2.49
5	Canister	15	0.10
6	Canister	Dry	1.00
7	Canister	5	0.74
8	Canister	10	0.42
9	Canister	15	0.14
10	Canister	20	0.02
11	Canister	16	0.54
12	Canister	7	1.11
13	Canister	3	1.99
14	Canister	5	1.04
15	Canister	8	0.77
16	Canister	10	0.51
17	Canister	12	0.25
18	Canister	15	0.23
19	Canister	20	0.14
20	Lucas Cell	Dry	1.00
21	Lucas Cell	5	2.42

TABLE 5-5 (Cont)

RADON FLUXES VERSUS TAILINGS MOISTURE CONTENT

Case	Measurement Type	Moisture Content (wt %)	Normalized Flux (ϕ / ϕ dry)
22	Lucas Cell	15	0.44
23	Lucas Cell	Dry	1.00
24	Lucas Cell	5	2.52
25	Lucas Cell	10	1.45
26	Lucas Cell	15	1.57
27	Lucas Cell	20	0.59
28	Lucas Cell	16	2.32
29	Lucas Cell	7	1.74
30	Lucas Cell	3	1.67
31	Lucas Cell	5	1.51
32	Lucas Cell	8	1.50
33	Lucas Cell	10	1.46
34	Lucas Cell	12	1.45
35	Lucas Cell	15	1.11
36	Lucas Cell	20	0.25

TABLE 5-6

CONCENTRATION AND FLUX VERSUS WIND SPEED DATA

1	2	3	4	5	6	7	8	9	10
Case	Pump Flow Rate (cc/sec)	Inlet Flow Rate (cc/sec)	Windspeed (Based on Col. 2) (cm/sec)	Windspeed (Based on Col. 3) (cm/sec)	Effective Windspeed (Col. 4- Col. 5) (cm/sec)	Measured Radon Concentration in HASL Flask (10^{-13} Ci/sec)	Total Radon Flux (Based on Col. 4) (10^{-13} Ci/cm ² sec)	Calculated Radon Flux (Based on Col. 6) (10^{-13} Ci/cm ² sec) (Pump Suction)	Net Radon Flux Due to Wind (10^{-13} Ci/cm ² sec)
1F	54	43	13.7	10.9	2.8	3.49	47.6	34	13.6
2F	17	14	4.4	3.7	0.7	5.09	22.6	15	7.6
3F	5	4	1.3	1.1	0.2	8.90	11.3	6	5.3
4F	2	1	0.4	0.3	0.1	18.61	7.3	3	4.3
5F PS	17	0	4.4	0	4.4	10.39	46.1	46.1	--
6F PS	11	0	2.9	0	2.9	11.95	34.5	34.5	--
7F PS	4	0	0.9	0	0.9	21.00	19.7	19.7	--
8F PS	2	0	0.4	0	0.4	24.83	9.7	9.7	--

F indicates with vertical flange on wind chamber

PS indicates inlet blocked, pure suction through tailings

TABLE 5-7

EXHALATION REDUCTION USING SURFACE STABILIZERS

<u>Sample Composition</u> ^(a)		<u>% Exhalation Reduction</u> ^(b)
<u>Mixture (%)</u>	<u>Materials</u>	(Range observed over several weeks)
	Control	0
50/50	PVAC/H ₂ O	0-20
50/50	3494/H ₂ O + 6% H ₃ PO ₄	0-40
25/25/50	3325/6600/H ₂ O + 3% H ₃ PO ₄	0
50/50	3325/H ₂ O + 6% H ₃ PO ₄	10-20
50/50	E-461/H ₂ O	0
50/50	E-461/PVAC	70-80
25/25/50	3325/E-461/H ₂ O + 3% H ₃ PO ₄	0-20
50/50	E-461/H ₂ O	0-60
50/50	E-461/H ₂ O	0
67/33	PVAC/H ₂ O	30-40
25/25/50	3325/E-461/H ₂ O + 3% H ₃ PO ₄	0-20
50/50	6600/H ₂ O + 10% DBP	0-50
10/90	AM-9/H ₂ O + AP + DMAPM	50-70
	FR-3	40-60
	FR-450	0-60
	3325	0-20
50/50	UF-B/H ₂ O	0-20
	3325	0-10
50/50	UF-B/H ₂ O + 20cc 6600	10-40
50/50	UF-B/EA-11-086	0-20
50/50	UF-B/EA-11-086 + GPG	10-30
50/50	4436 + GPG/H ₂ O + 3% H ₃ PO ₄	0
50/50	4436/H ₂ O + 3% H ₃ PO ₄	0
50/50	Stab U/H ₂ O	0-20
50/50	4436/H ₂ O	0
75/25	E-461/UF/H ₂ O	10-50
25/25/50	E-461/UF/H ₂ O	40
50/50	6600/H ₂ O	30-50
25/25/50	TREX/6600/H ₂ O	20-30
50/50	E-461/H ₂ O + VA-104	0
	Control	0
	E-63 Asphaltic Emulsion	95

(a) Compound names indicated specific organic materials obtained from commercial vendors for testing.

AM-9 - Dow Chemical

6600 - Borden Company

E-461 - liquor of lignin

UF - Ultrafoam

(b) 100 x (1 - ϕ treated/ ϕ untreated)

TABLE 5-8

IN-SITU TEST OF SURFACE STABILIZERS

<u>Sample Composition</u>	<u>Surface Fluxes (10^{-15} Ci/cm²-sec)</u>	<u>% Exhalation Reduction After 1 Week</u>
50/50 E-461/TREX	1.72 $\pm$ 0.67	53
50/50 6600/H ₂ O	1.32 $\pm$ 0.75	64
50/50 UF/H ₂ O	0.86 $\pm$ 0.19	77
Control	3.68 $\pm$ 2.83	0

TABLE 5-9

COMPOSITION OF CHEMFIX VOLUMETRIC
CHEMICAL STABILIZER SAMPLES

<u>Number</u>	<u>Description</u>	<u>Weight of Reagents (kg)</u>			
		<u>Tailings</u>	<u>Water</u>	<u>Cement</u>	<u>Silicates</u>
1066	Sandy tailings, stabilized	7.2	7.2	2.0	1.1
1067	Stabilized sandy tailings on top of 7.2 kg of dry sandy tailings	7.2	7.2	2.0	1.1
1068	Fine tailings, stabilized	5.5	8.3	1.3	0.6
1092	Clean mortar over dry tailings (2.5 kg of sand)	4.0	5.0	1.7	0
1093	Stabilized cement over dry tailings	4.0	5.5	0.9	0.6
1094	Same as 1093, except 1 kg water saturating tailings	4.0	6.5	0.9	0.6
1095	Same as 1094 with modified stabiliz- ing mixture	4.0	5.0	2.1	0.9

TABLE 5-10

EXHALATION REDUCTION USING CHEMFIX
VOLUMETRIC CHEMICAL STABILIZER

Sample No.	Sample Composition (kg)				% Exhalation Reduction
	Tailings	H ₂ O	Cement	Silicate	
1066	7.2	7.2	8.0	1.1	50
1067	7.2	7.2	2.0	1.1	70
1068	5.5	8.3	1.3	0.6	0
1092	4.0	2.0	5.0	0	90
1093	4.0	5.5	0.9	0.6	70
1094	4.0	6.5	0.9	0.6	40
1095	4.0	6.1	1.6	0.8	50
1096	4.0	4.0	2.1	0.9	50

TABLE 5-11

RADON EXHALATION TEST SPECIMENS

(Ford, Bacon & Davis, Inc. - Vitro Tailings)

Date Made	Test No.	Description and Sample Preparation	% Solids	% Additions Based on wt % Solids	
				Calcilox	Ca(OH) ₂
12/23/76	432-1	No. 1 to 5	40	0	0
12/23/76	-2	Combine as received	40	5.0	1.0
1/ 6/77	-3	Tailings with tap water	40	7.5	1.0
1/ 6/77	-4*		40		
1/ 6/77	-5*		40		
1/ 6/77	-6	No. 6 to 10	40	0	0
1/ 6/77	-7	Combine as received	40	5.0	1.0
1/ 6/77	-8	-50 mesh tailings	40	7.5	1.0
1/ 6/77	-9*	With tap water	40		
1/ 6/77	-10*		40		
1/ 6/77	-11	Combine as received	40	5.0	1.0
1/ 6/77	-12	+50 mesh tailings	40	7.5	1.0
1/ 6/77	-13	With tap water	40		
	-14	Compacted at Proctor	85	0	0
	-15	Dynamic Compaction	85	5.0	1.0
	-16	With 5.5 lb hammer	85	7.5	1.0
	-17	12,400 ft-lb/ft ³ on	85		
	-18	As received tailings with tap water	85		

*Proprietary additive substituted for Calcilox

TABLE 5-12

DRAVO LIME CALCILOX SAMPLE TEST RESULTS

<u>Sample No.</u>	<u>Surface Flux (fCi/cm²sec)</u>	<u>% Exhalation Reduction</u>
432-1-A	0.87	60
-1-B	0.82	70
-2-A	1.05	60
-2-B	0.72	70
-3-A	0.42	80
-3-B	0.54	80
-4-A	0.41	80
-4-B	0.18	90
-5-A	0.80	70
-5-B	0.98	60
-6-A	0.98	60
-6-B	0.32	90
-7-A	0.62	80
-7-B	2.23	10
-8-A	0.64	70
-8-B	1.10	60
-9-A	0.36	90
-9-B	1.17	50
-10-A	0.84	70
-10-B	0.36	90
-11-A	0.14	90
-11-B	0.06	98
-12-A	0.23	90
-12-B	0.32	90
-13-A	0.24	90
-13-B	0.05	98
-14-A	0.81	70
-14-B	1.34	50
-15-A	1.39	40
-15-B	1.48	40
-16-A	0.90	60
-16-B	1.26	50
-17-A	1.17	50
-17-B	1.03	60
-18-A	1.26	50
-18-B	1.48	40
Untreated tailings	2.50	

Date samples were tested: 2 March 1977

TABLE 5-13

NET GAMMA-RAY BUILDUP IN COVER MATERIAL
AS A FUNCTION OF DEPTH

Cover Material Depth (ft)	Average Background	Net Counts	
		With Radon Diffusion	Without Radon Diffusion
0	4488 $\pm$ 67	2343 $\pm$ 83	--
1	1365 $\pm$ 37	622 $\pm$ 44	591 $\pm$ 44
2	1330 $\pm$ 36	135 $\pm$ 38	132 $\pm$ 37
3	1346 $\pm$ 37	70 $\pm$ 38	59 $\pm$ 37

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This section summarizes the main conclusions derived from the experimental results and lists recommendations for further study and evaluation.

6.1.1 Emanating Power

Experimental measurements of the emanating power of Vitro uranium mill tailings from the Salt Lake City site indicate that the emanating power for these tailings is about 20%. For a sample separated as a function of tailings particle size, there is a weak trend indicating that the largest emanating powers are associated with the smallest particle sizes that have the highest surface-to-volume ratios. However, the variation in emanating power with particle size is remarkably small. Leaching the tailings with additional acid washes tends to increase the emanating power perhaps by removing the outer weathered mineralization surfaces and exposing fresh surfaces from which the radon escapes more readily.

6.1.2 Radon Soil Gas Concentrations in Cover Materials

The experimental measurements of radon soil gas concentrations from sand and bentonite cover over uranium mill tailings generally conformed with theoretical expectations. The effective diffusion coefficient that fit the experimental and analytical results is $3 \times 10^{-2} \text{ cm}^2/\text{sec}$ for both tailings and cover materials. The experiments verified the applicability of diffusion theory in modeling radon transport through tailings and cover materials.

6.1.3 Surface Radon Flux as a Function of Tailings Depth

Measurements of surface radon fluxes from various depths of uranium mill tailings agreed with previously derived predictions. The flux approaches its maximum value at about 10 to 12 ft of tailings thickness. Greater depths of tailings do not contribute significantly to the surface flux.

6.1.4 Effects of Cover Material Thickness on Radon Exhalation

The surface fluxes were determined for different thicknesses of cover materials. The relationships derived from the experimental data are about a factor of two less than theoretical predictions because of the inability of Fick's law of diffusion theory to adequately describe events near a vacuum boundary and the difficulty of measuring the radon concentration at the interface. Empirical analysis of the radon soil gas concentrations

does give good correlation with the experimentally observed flux behavior.

6.1.5 Effects of Absolute Temperature and Pressure on Radon Flux

The experimental measurements at different temperatures and pressures indicate that binary gas diffusion laws appear to be appropriate for describing radon gas transport through tailings. Variations in absolute temperature and pressure over environmentally expected ranges will not cause changes in the steady state fluxes of more than about $\pm 10\%$, but transient effects may be large.

6.1.6 Effects of Moisture in Tailings on Surface Radon Flux

Moisture in the tailings decreases the available pore space for diffusion and absorbs the radon gas. The radon flux values are related to the evaporation rate of the moisture and to the moisture content. It appears that adding moisture to dry tailings first increases the surface fluxes, then decreases them as more moisture is added. When drying out, the flux also appears to increase when the evaporation rate is high.

6.1.7 Effects of Windspeed on Surface Fluxes

Under laboratory experimental conditions, surface radon flux increases with increasing windspeed. Sweeping of the near surface air volume increases the radon concentration gradient, which enhances the flux. In addition, a Bernoulli pumping effect, removing tailings gases because of a pressure differential, is also important. However, a correlation between varying field windspeeds and resultant changes in surface radon fluxes is difficult to precisely quantify because of irregularities in environmental surface features, obstacles, contours, and windspeed gradients near the ground surface.

6.1.8 Effects of Chemical Stabilizers on Radon Surface Fluxes

Both surface and volumetric stabilizers were evaluated for their effectiveness in reducing radon surface exhalation. The surface stabilizers are about as effective as volumetric stabilizers, and are easier and cheaper to apply. Several materials were identified that show promise as effective radon barriers in the short term; however, effects of weathering over long-time periods have not been investigated.

6.1.9 Gamma-Ray Buildup in Cover Material

A series of measurements were made to determine if establishment of radon gas and daughter concentrations in initially "clean" cover material causes significant buildup of gamma-ray intensities. No substantial buildup was observed in any of the experimental configurations devised to investigate this phenomenon.

6.1.10 Vegetative Stabilization

Plants were found that can grow in tailings and through cover material/tailings interfaces if sufficient water and fertilizer are available. The effect of vegetation on radon exhalation, however has not been clearly demonstrated. Root penetration could provide additional pathways for radon diffusion to the surface.

6.2 Recommendations for Further Study

6.2.1 Variations in Diffusion Coefficients

Effective diffusion coefficients for migration of radon gas through various media partially determine the radon exhalation rates. Variations in the materials through which the radon passes, such as changes in porosity, moisture content, cover density and compaction, will change the radon surface fluxes. These effects should be investigated.

6.2.2 Effects of Moisture on Radon Fluxes

Not only do moisture variations cause changes in effective radon diffusion coefficients, these variations also affect the amounts of radon dissolved, the effective crystalline surface area for emanation, and possibly other mechanisms for changing the fluxes. Rates of addition and evaporation of moisture appear also to affect the fluxes. These effects should be investigated in more detail for both tailings and cover materials to obtain an understanding of the importance of moisture in controlling radon exhalation. Investigation of the effects of moisture on the measurement techniques is also required to explain observed differences in methods.

6.2.3 Chemical Stabilizers

If chemicals can be found that are effective radon diffusion barriers when applied to tailings or cover materials, many potential health effects from uranium mill tailings could be avoided by trapping the radon gas and preventing its escape to the atmosphere. More testing of materials is needed to determine effectiveness and long-term weathering and cycling effects. Coordination and comparison of the results of testing by various government agencies now involved in stabilization testing is also desirable to maximize efficient selection of suitable stabilizers.

6.2.4 Radon Emanating Power

Further investigation of the factors influencing the radon emanating power of mill tailings is required to provide a basis for predicting radon exhalation from different types of ores, mining, and milling operations.

6.2.5 Vegetative Stabilization

Vegetative cover is very effective in reducing wind and water erosion of tailings and covers over tailings. However, penetration of roots through tailings, formation of root tubes, and possibly radium uptake by the plant systems could adversely effect the radon exhalation from tailings. Further testing is required to allow proper plant selection and prediction of long-term effects on radon exhalation.

6.2.6 Transverse Radon Transport

One dimensional diffusion theory prediction appears adequate to explain experimental results so far observed. However, placing diffusion barriers over tailings piles may cause transverse migration, enhancing the importance of leakage and edge effects. These effects should be investigated to allow prediction of cover effectiveness and assessment of the effects of future cover penetrations.

6.2.7 Gamma-Ray Hazards

The buildup of gamma-ray intensities as a result of adding radon barriers (thus collecting increasing radon concentrations under the barrier) need to be investigated to assure that cover thicknesses are adequate for gamma-ray protection. Other mechanisms for gamma ray buildup should also be investigated.

6.2.8 Effects of Changing Pressures on Surface Fluxes

Steady state dependences on absolute pressure have been determined. However, transient effects arising from changes in atmospheric pressure require further evaluation. Because of the difficulty in controlling all factors that affect the radon fluxes in the field, these experiments should be performed under controlled laboratory conditions.

APPENDIX A
VEGETATIVE STABILIZATION REPORT

By

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Site Preparation and Planting

Preparation of an appropriate site on the Vitro tailings, Salt Lake City, for revegetation trials was initiated and completed during the first two weeks of June 1976.

The area prepared is approximately one-hundred by fifty feet. Plowing followed by tilling was required in order to enhance the physical properties of the tailings such that they would better promote plant growth. Five subplots of about twenty by fifty feet were made to correspond to five fertilizer treatments i.e.,

#1 - $\text{NH}_4/2 \text{ NO}_3$

#2 - Urea

#3 - NPK

#4 - $\text{NH}_2 \text{ SO}_4$

#5 - Control

Each subplot was fertilized accordingly by broadcast fertilization and then furrowed and seeded with the following grass species.

1. Resistador Alfalfa
2. Regar Brome Grass
3. Topar Pubescent Wheatgrass
4. Orchardgrass
5. Siberian Wheatgrass
6. Tall Wheatgrass
7. Perennial Ryegrass
8. Nordan Crested Wheatgrass
9. Tegmar Wheatgrass
10. Crested Wheatgrass
11. Alta Tall Fescue
12. Red Clover

One row of each grass was planted per subplot.

In addition, an area without fertilizer treatment was planted (whole plants) with hybrid species of Cynadon (Bermuda grass) and Paspalum (Torpedo grass).

Water Delivery

In order to maintain sufficient soil moisture to effectively promote seed germination and seedling survival, about two thousand gallons of water was applied to the site per week. This water demand reflects the lateness of the seedings. Ordinarily such seedings would be done in late April or early May if done in the spring time. If done in the fall middle September would be the desired seeding time. Water was applied in approximately seven-hundred and fifty gallon increments three times per week. To carry out the watering required renting a flat-bed truck and mounting an appropriate water tank. Additionally, a water pump and considerable hosing and nozzles were acquired. One watering including preparation time and dismantling of equipment required six hours for two men. Truck rental charges were \$135/week. Cost of hoses, pump and nozzles, and accessories is estimated at about \$1,000. Because of the substantial cost of watering, the treatment was limited to five weeks or to early July. At this time temperatures became exceedingly high (air 95°F to 103°F) (soil surface 125°F to 150°F). In order to maintain sufficient plant moisture under these conditions it was judged that watering would be required on a daily basis at the 750 gallon level. This is impractical under the circumstances. Thus only spring or fall plants are practical.

Evaluation of Growth

In all subplots all grasses seeded germinated profusely and survived so long as the water treatments continued. The hybrid plantings (whole plants) continue to grow and are expected to survive the summer weather. The toughest test for these hybrids will be winter survival since their parent plants naturally evolved under an exceedingly hot climate but mild winter.

There seems to be little doubt that the seeded species would continue their growth provided optimum moisture is available. We saw no evidence of marked or critical toxicity symptoms. However, these may appear with longer growth.

Late Summer/Fall Planting

The subplots as described in progress report #1, July 1976, were planted with young, laboratory germinated, seedlings August 20, 21. One hundred individuals were planted per thirteen (13) different grass species and 100 clover plants. That is, some fourteen-hundred (1400) individual plants were planted. The species planted were:

- Resistador alfalfa (Medicago)
- Regar brome grass (Bromus)
- Topar pubescent wheatgrass (Agropyron)
- Orchardgrass (Dactylis)
- Siberian wheatgrass (Agropyron)
- Tall wheatgrass (Agropyron)
- Perennial ryegrass (Lolium)
- Nordan crested wheatgrass (Agropyron)
- Tegmar wheatgrass (Agropyron)
- Crested wheatgrass (Agropyron)
- Alta tall fescue (Festuca)
- Alfalfa (Medicago)
- Bermuda grass (Cynadon) (hybrid)
- Torpedo grass (Paspalum) (hybrid)

It was decided that probably plantings of this type could be safely made in the late summer in spite of little water availability other than that which might come as rain or residual in the tailings pile. After approximately one month most individual grasses appeared to have survived and many had put on limited, but new growth. In contrast most of the alfalfa plants appeared to be dying. It should be noted that during this one-month period little or no

significant rainfall occurred on the plots. It may be concluded that virtually only residual moisture was available to the plants.

The key factor here is considered to be soil moisture availability which is of course a function of the precipitation/evaporation ratio (P/E) and plant transpiration. During late summer the maximum daily temperatures of the soil surface fall below 100°F whereas in mid-summer daily values ranging over 130°F are encountered. The P/E ratio is very much a function of soil surface temperature. A practice which we feel is a valuable aid in retarding plant transpiration (water loss) is simply to trim or cut the plant shoots after planting. Clearly the clipped plants appear more vigorous than those not clipped. This treatment is also known to stimulate root growth providing the cutting is not too drastic.

It should also be mentioned that our observations indicate two basic types of tailings with respect to textural type. That is, the tailings seem to be either of relatively high clay content or high in sand. The clay type, of course, has a much greater water holding capacity and in this case seems to provide more plant-available moisture than the sandy type. Water stress was observed to be greater in the sandy tailings as opposed to the clay type. Also there appears to be more "salting out" on the surface of the sandy areas than the clay. This apparent effect should be investigated as it appears to be compounding the moisture stress effect associated with the sandy type. About three man-days were required to complete the plantings.

Fall Seeding

The same subplots were seeded with the same species utilized in the plantings except wild sweet clover, Melilatus, was substituted for alfalfa. The seeding was just completed (September 23, 1976) at the time of this writing, and thus it is too early to make an evaluation as to its success or

failure. Approximately one man-day was required to complete the seeding.

Additional Field Studies

In peripheral areas of the Vitro tailings we discovered an annual grass "barnyard grass" (Echinochloa crusgalli) growing successfully on unamended tailings. Subsequently we obtained seed of this grass and broadcast seeded a plot adjacent to our main plot. This grass germinated well and has grown to maturity, and is now forming seeds. No fertilizer was added to this second plot.

Photographic Description

Photos and accompanying descriptions are appended here, and attest to the effort to date.

General view of all plots with plot #1 in foreground.

General view of plot #1.

Alta tall fescue - plot #1.

Siberian Wheatgrass - plot #1.

Alfalfa - exhibited good vigor after 4 weeks - appears to be less vigorous after 6 weeks.

Perrenial rye grass - plot #1.

Crested wheatgrass - plot #1.

Rabbit droppings. As growth progresses rabbits tend to come into plots and graze.

General view of extensive
rhizomatous growth of several
Cynodon dactylon plants.
Plot #3.

Cynodon dactylon (African hybrid) showing extensive shoot growth. Plot #3.

Paspalum vaginatum (African hybrid) showing rhizome growth. The prominent rhizome is about 2 feet long. Plot #3.

General view of barnyard grass.
Plot #7.

Individual plant of barnyard grass.
Plot #7.

- Several plants of barnyard grass.
Plot #7.

Closeup of barnyard grass showing seed stalk. Plot #7.

Greenhouse Growth Studies

During October, 1976 soil columns were prepared to test the growth of perennial grass species in soil, Vitro mine tailing and in soil laid over tailings. The purpose of these studies is to determine the extent of root and shoot growth in the tailing with and without a soil cover. In addition Ford Bacon and Davis will monitor these columns for variation in radioactive emissions. Thus, these experiments should ultimately provide clues to the effects of root penetration into the tailing with respect to the flux of radioactive emissions. It is a possibility, for example, that the death and decay of roots may enhance emissions due to the vacant root channels. Also, rooting itself may induce considerable cracking which conceivably could lead to increased emissions.

The following describes the prepared soil columns. Each column was contained in a metal cylinder about 3' long x 6" diameter. A window was made in each cylinder to permit observation of root growth at the interface between soil and tailings. A clear plastic was used to seal the windows. During growth the windows are covered to prevent light effects on the roots. Two sets of plantings were made:

SET I

Twelve inches of soil over twenty-four inches of tailings; 3 subsets planted to Cynadon dactylon and 3 planted to Paspalum vaginatum.

SET II

Similar to SET I except no soil cover was used.

The Paspalum was planted October 20, 1976 and the Cynadon on November 10, 1976.

In all instances the plants exhibited root growth into the tailings. Since we do not want to destroy the columns at this time it is impossible to provide a truly quantitative estimate of this growth. However, based on the "window" observations we estimate the root growth of Paspalum through the soil layer required about two weeks (per 12 inches of soil) and in a total time of about five weeks penetrated four to six inches into the tailings. There was little or no lateral root spreading observed at the interface. It appears even the difference in the physical properties of the two layers had little material affect on root penetration. Also the roots observed showed extensive primary and secondary growth and normal root hair development.

Although planted some twenty days later than the Paspalum, the Cynadon roots had also grown through the soil layer and penetrated the tailings without showing lateral growth at the interface. But, and probably a result of the later planting, the Cynadon roots had penetrated only about two to three inches into the tailings and generally lacked in secondary growth although root hairs were perfuse. Shoot growth was extensive in both species during this period of growth.

In those columns without the soil cover the roots have not, as of this writing, penetrated the twelve or so inches such that they may be observed in the "windows." However, parallel pot studies wherein both species of plants were placed directly on tailings contained in plant pots have demonstrated perfuse root growth throughout the tailings.

The overall impression at this time is that root growth may be somewhat slowed as it impinges upon the tailings at interface but that the general growth

is nevertheless extensive within the tailings. As seen through the "windows" there is no obvious evidence that the roots tend to form mats or otherwise exhibit abnormal growth forms.

pH Measurements

Tailing samples obtained from the field plots were brought to the laboratory and subsamples diluted 2:1 with distilled water and mechanically shaken for 20 minutes and the solid phase allowed to settle. pH determinations were then made on the resulting supernatants. These data follow for:

- 1 - Plot #'s 1 through 5: In and Outside i.e., in fenced area, outside fence but adjacent.
- 2 - Ec = Echinochloe plot
- 3 - Salt crust - crusted areas

In general, the pH values all tended towards ca pH 4.0 except in the Ec plot which approximated pH 4.9 to 5.0. No explanation is really clear but we may find this area has had other kinds of overburden added as have many sites on the Vitro tailings.

Vitro pH Measurements (1:2) 50_g Soil:100ml HOH

Sample #	1st Rep.	2nd Rep.	Avg.	
1	3.99	4.08	4.04	
2	4.03	4.02	4.03	} outside main plot!
3	4.05	4.04	4.05	
4	4.04	3.89	3.97	
5	3.91	3.94	3.93	
Ec Plot	5.01	4.88	4.95	
Ec Plot	4.97	4.81	4.89	
Salt Crust Plot 1	3.92	3.93	3.93	
Salt Crust Outside	3.94	3.94	3.94	
Subplot				
1 In	3.84	3.90	3.87	
1 Out	3.94	3.94	3.94	
2 I	4.08	4.14	4.11	
2 O	4.31	4.27	4.29	
3 I	3.89	3.91	3.90	Avg. I = 4.01 O = 4.04
3 O	3.95	3.99	3.97	
4 I	4.12	4.13	4.13	
4 O	4.13	4.11	4.12	
5 I	4.04	4.00	4.04	
5 O	3.89	3.90	3.90	

pH deionized H₂O = 5.75

This report provides photographic evidence attesting to the growth of our hybrids of Cynadon spp. and Paspalum spp. in Vitro tailings. The procedures are outlined in previous reports. Briefly, cylinders are filled with about 2 feet of tailings and then an additional 9 inches of native soil is layered on the tailings. Seedling plants are planted in the soil and watered only occasionally. No other additions are made. Two types of cylinders are used, metal and waxed cardboard. The former have a "window" cut out such that the interzone between soil and tailings is visible. The cardboard type is used because they may be opened easily for observation.

The basic information we wanted relates to root activity in the interzone and degree of penetration into the tailings. The plants reported on here had been growing about two months at the time of photographing.

Figures 1 and 2 show root growth of Paspalum and Cynadon respectively in metal cylinders. Root growth in Paspalum appears to be more extensive than in the Cynadon. However, this is not really the case as the roots of the latter just didn't permeate the window region to the degree seen for the Paspalum. It is obvious shoot growth was also extensive. Some of the stems seen in Fig. 1 attained over 3 feet of growth while some of those in Fig. 2 measured almost 5 feet. We found no evidence of the roots "spreading out" in the interface between soil and tailings. Figure 3 is a close-up of a typical interface (in this case the species is hybrid Cynadon). It can be seen that root penetration exceeded well beyond six inches of tailings. Also note there appears to be no "deflective" growth at the interface. Figure 4 is illustrative of even greater root growth in Paspalum. It is evident the roots have outgrown the cylinder. The roots then have grown more than the length of the entire tube i.e., 26 inches. This represents about 15 inches of overall vertical growth through the tailings alone.

Figure 1. Paspalum

Figure 2. Cephradon

Figure 3. Cephradon

Figure 4. Paspalum

These experiments have been replicated six times and the evidence shown herein is consistent among the replicates. The studies as well as the field trials indicate the in situ tailings in all probability can be stabilized with several grass species we have studied. To date we can recommend the Cynadon and Paspalum types for perennial vegetation. We recommend Echinachlæe crusgalli (barnyard grass) for an annual cover. This latter species seeds itself on some field sites on the actual tailings. The other grasses seeded and planted in the field have varying degrees of potential but cannot be adequately judged until the resumption of this year's spring and summer growth.

The Cynadon and Paspalum grasses growing on tubes of soil covered tailings were monitored for radiation emittance after ca. 3 months growth (see previous progress reports, particularly No. IV for details of preparation).

The average emittance recorded through the planted soil cover was 0.02 milliroentgens per hour while that emitted in the absence of the soil and plants was 0.15. The set of samples with a soil cover only (no plants) emitted ca. 0.02. Thus the reduction in emittance is attributable to the soil cover, and the penetration of plant root appears to have no measurable effect on emittance. (The values are means of six replicates for beta and gamma rap.)

The soil, tailings and grasses are to be concentrated into different samples and analyzed for the full spectrum of radiation. This is being done by our Department of Radiological Health and will be forwarded as available.