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J. N. Hartley
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Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-3290

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy $_______*; Microfiche $3.00

*Pages	NTIS Selling Price
001-025	$4.00
026-050	$4.50
051-075	$5.25
076-100	$6.00
101-125	$6.50
126-150	$7.25
151-175	$8.00
176-200	$9.00
201-225	$9.25
226-250	$9.50
251-275	$10.75
276-300	$11.00

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ASPHALT EMULSION SEALING OF URANIUM MILL TAILINGS

1979 ANNUAL REPORT

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ABSTRACT

Uranium mill tailings are a source of low-level radiation and radioactive materials that may be released into the environment. Stabilization or disposal of these tailings in a safe and environmentally sound way is necessary to minimize radon exhalation and other radioactive releases. One of the most promising concepts for stabilizing uranium tailings is being investigated at the Pacific Northwest Laboratory: the use of asphalt emulsion to contain radon and other potentially hazardous materials in uranium tailings.

Results of these studies indicate that radon flux from uranium tailings can be reduced by greater than 99% by covering the tailings with an asphalt emulsion that is poured on or sprayed on (3.0 to 7.0 mm thick), or mixed with some of the tailings and compacted to form an admixture seal (2.5 to 15.2 cm) containing ~18 wt% residual asphalt.

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SUMMARY

The Department of Energy contracted the Pacific Northwest Laboratory to evaluate asphalt emulsions as a sealant to retain radium and other potentially hazardous materials in uranium tailings and to prevent radon exhalation to the atmosphere. Both laboratory and field studies are in progress. Laboratory studies include tailings characterization, seal formulation, radon diffusion measurements, and assessment of seal stability. Field studies include evaluation of application technology and field tests to determine the effectiveness of sealing procedures.

The results of this study during Fiscal Year (FY) 1979 (Oct. 1, 1978, to Oct. 1, 1979) are summarized below.

LABORATORY STUDIES

- A radon flux reduction of greater than 99% was achieved by using either a 3- to 7-mm poured-on cationic asphalt emulsion seal or a 7.6 cm compacted admixture seal of tailings and emulsion containing 18 to 20 wt% residual asphalt. Admix seals containing less than 18 wt% residual asphalt did not provide a total seal. Armak Co. E-63, E-65 and E-4868 cationic asphalt emulsions were used to prepare the seals.
- Tailings samples from the tailings pile at Grand Junction, Colorado, were tested using both poured-on and admix sealing procedures. Samples from Tuba City, Monument Valley, Shiprock, and Falls City were tested only with the poured-on seal.
- Radon fluxes through the admix seals containing 18 to 20 wt% asphalt were about 0.68 $pCi/m^2 \cdot s$, representing a flux reduction of greater than 99% for nitrogen/radon gas pressures maintained at about 0.3 psi.
- The physical-chemical properties of the tailings had a significant effect on seal formation. Tailings containing clay like, high-surface-area materials, such as those with greater than 30% of these

materials passing a 400-mesh screen, are very difficult to seal with an admix seal. A high clay content in the tailings can result in poor mixing due to agglomeration of fine particles, thus making it difficult to form an admix seal. A very low zeta potential (+20 mV) cationic emulsifier is needed to penetrate material agglomerations and completely coat the particles with a continuous film.

- Based on the laboratory studies, an admix seal containing 18 to 20 wt% residual asphalt with a low zeta potential (+20 mV) cationic asphalt emulsion was recommended for the initial field test. The moisture content of the tailings must be about 7 wt% to ensure good penetration and particle coverage and to preclude premature emulsion dehydration. Tailings with greater than 30% of the 400-mesh particles present extreme mixing problems and cannot be sealed directly. They must either have the fines removed, or a coarser material, such as a local sand, must be placed over the tailings to provide a surface that can be successfully sealed with the admixture method.

FIELD STUDIES

A field test was carried out at the Grand Junction tailings pile in June 1979. A reduction in radon flux ranging from 4.5 to greater than 99% (76% average) was achieved using a 15.2-cm (6-in.) admix seal (Armak Co. E-4868 emulsion and tailings) with a sprayed-on top coat. A soil stabilizer was used to apply the asphalt emulsion. This application was followed by compaction and a fog seal to form the radon seal. A 10- to 12-in. cover of overburden was applied over about two-thirds of the test area to protect the seal from mechanical abuse and weathering. The other one-third of the test area was left exposed to the environment in order to investigate degradation of the seal by ultraviolet radiation (UV), etc. A herbicide Treflan® was applied to one part of the covered test area in order to prevent root penetration. Results of the field test indicate the following:

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- A radon seal can be obtained if a proper admix seal is applied. Unfortunately most of the sealing of tailings was achieved with the top coat since the admix did not contain the required 18 to 20 wt% residual asphalt. The seal only had 9 to 15 wt% residual asphalt as a result of poor depth control during seal application and compaction. This problem probably can be solved by equipment modifications and improved compaction.
- A lack of water applied to the tailings caused difficulties in tailings compaction. Also, more water was needed in the tailings prior to admixing in order to prevent premature emulsion dehydration during seal formation. Prior to spraying the top coat over the admix seal, the water truck pump failed. The only available substitute could not spray water. As a result, the admix surface was not adequately wetted before applying the top coat, resulting in a poor bond between the admix seal surface and the top coat.

INTRODUCTION

The milling (extraction) of uranium ore produces large quantities of waste (mill tailings) which remain potentially hazardous for a long time due to the long half-lives of the radionuclides present. The two potentially hazardous radioactive decay products are radium-226 (half-life 1620 years), a solid, and radon-222 (half-life 3.8 days), a radioactive gas which is considered to present the most significant exposure risk.

Based on projected U.S. nuclear generating capacity, 490 million metric tons (MT) of tailings may be produced by the year 2000 using conventional milling.(1) These tailings would be in addition to the 107 million MT of tailings at currently active mill sites at the end of 1977 and 22.8 million MT of tailings at inactive sites. Because of potential radiation health hazards to the public, methods to stabilize or dispose of the tailings in a safe and environmentally sound manner are needed in order to minimize radon exhalation and other environmental hazards.

Proposed requirements for uranium tailings disposal include placing no less than 3 m (10 ft) of cover material over the tailings.(1) This cover material (overburden) must not include mine waste or rock that contains elevated levels of radium. This technique might minimize human exposure from inhalation and ingestion, but it is not considered a totally satisfactory solution based on economics and the availability of cover material.

An alternative approach would be to apply a cost-effective cover material that would reduce radon exhalation to background levels and remain stable for at least 1000 yr. The Pacific Northwest Laboratory (PNL) is working on such an alternative.(2) The Department of Energy has contracted PNL to evaluate the use of asphalt emulsion sealants to retain radium and other potentially hazardous materials in uranium tailings and to provide a barrier over the tailings to prevent radon exhalation to the atmosphere. Figure 1 illustrates the general concept of stabilizing or sealing a tailings pile above or below grade using the asphalt emulsion sealing procedure.

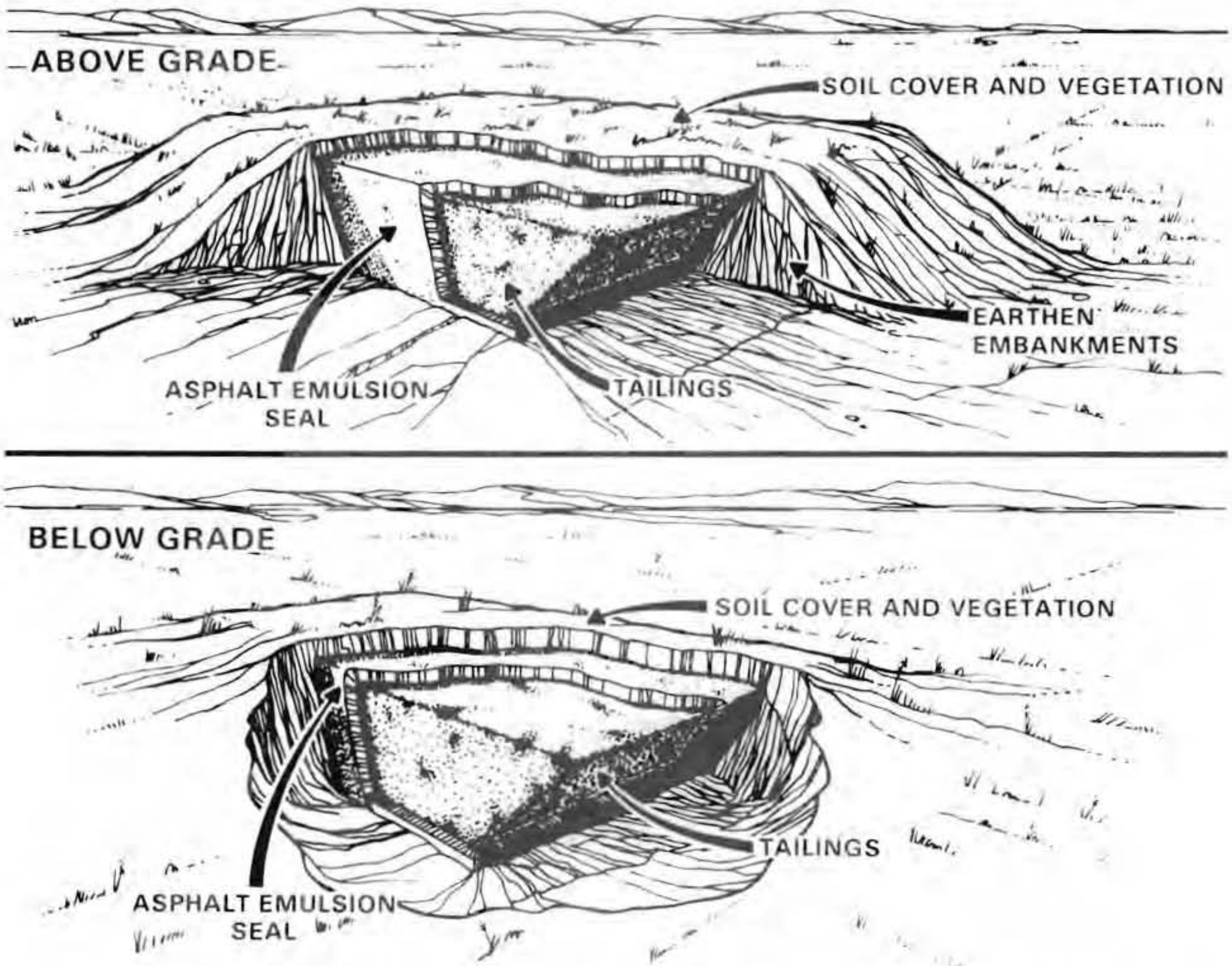

FIGURE 1. Disposal of Uranium Tailings Using an Asphalt Emulsion Seal

In order for a stabilization or sealing material to last for 1000 yr, it must be inert, remain pliable, and not be affected by its surrounding environment. Since no materials have been tested for greater than 19 to 100 yr we cannot provide long-term stability data.

We do know that asphalt, the primary constituent of asphalt emulsion, is present in very old (2500 to 5800 yr), roads, dams, reservoirs, canals, ornaments, figurines, and statues. Many of the Babylonian canals are still used today. The asphalt has remained in good condition over all these years. In addition many ceremonial objects have been excavated and recovered in excellent condition, attesting to the potential long-term stability of asphalt particularly when under anaerobic burial conditions. However, previous applications of asphalt did not involve obtaining a gas-tight seal.

The use of cationic asphalt emulsion to contain radon and other potentially hazardous materials within uranium tailings is being investigated in the laboratory and in field tests. Laboratory studies include uranium tailings characterization, asphalt emulsion formulation, radon diffusion measurements, and assessment of seal stability. The field studies include review and evaluation of application technology and field tests using the most promising application technology to apply an effective seal. The effectiveness of the asphalt emulsion seal to contain radon is being established by monitoring radon exhalation with time. The stability of the seal is being evaluated to determine the effects of chemical (oxidation, UV, radiation) and physical (mechanical, freeze/thaw, animal intrusion and root penetration) degradation.

This report discusses the progress of this project, including laboratory and field studies, and summarizes the status of the sealing procedure for controlling radon release from uranium tailings. The long-term stability of asphalt emulsions and the cost of potential tailings seals are also discussed. Both general and specific recommendations are made for additional research that would enhance DOE's options to stabilize and seal uranium mill tailings.

ASPHALT EMULSION

Asphalt emulsion consists of asphalt, water, and an emulsifier (surface-active agent or surfactant)[a] which are combined together in a colloid mill to form a homogeneous mixture of small asphalt droplets suspended in water (Figure 2).[4] The quality of asphalt and water used to make the emulsion is very important. However, the most important component of any asphalt emulsion is the emulsifier (surfactant).

To be an effective emulsifier for asphalt, the surfactant must be water soluble and must possess a proper balance between hydrophilic and hydrophobic

(a) Surfactants possess the unique property of altering the surface energy of their solvents, usually lowering rather than increasing the surface energy. Surface-active chemicals are soluble substances that markedly change the properties of their solvents and the surfaces they contact. The three basic types of chemical surface-active agents are classified according to their dissociation characteristics in water: anionic, nonionic, and cationic surfactants.

properties. When used in combination with an acceptable asphalt, a good-quality water, and adequate mechanical mixing, the emulsifier is the major factor which influences initial emulsification, charge type and intensity, emulsion stability, and ultimate field performance.

The asphalt emulsions considered for sealing tailings are cationic asphalt emulsions that have positively charged droplet surfaces. The positively charged surface of the asphalt droplets adhere to the negatively charged tailings as shown in Figure 2. The surface charge (zeta potential) of cationic asphalt emulsions ranges from +12 to +130 mV. The choice of cationic emulsion depends on the surface area (particle size distribution) and surface charge (zeta potential) of the material to be sealed. Materials with different particle size distributions and surface charge may require different choices of asphalt emulsion in order to obtain the proper bonding, set time, and penetration.

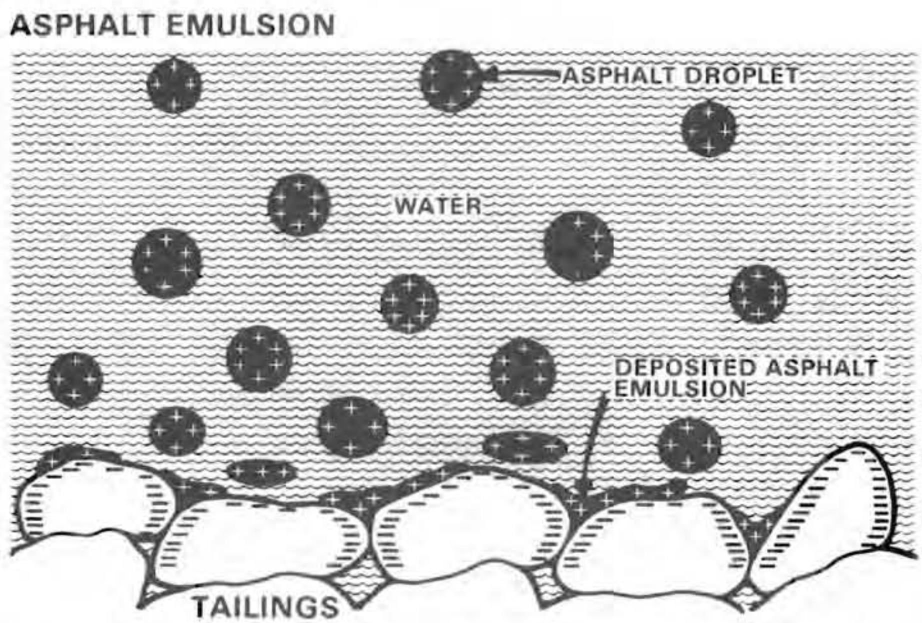

FIGURE 2. Asphalt Emulsion Deposition on Uranium Tailings

LABORATORY STUDIES

The overall objective of the laboratory studies is to investigate various asphalt emulsion sealants to contain radon and other potentially hazardous materials including radium in the uranium mill tailings. Characterizing uranium tailings, formulating the seal, measuring radon diffusion, and evaluating the stability of the seal are the primary activities.

URANIUM MILL TAILINGS CHARACTERIZATION

Table 1 lists the 25 inactive uranium tailings sites, their operational periods, quantity of tailings, radium content, acreage, and the uranium recovery process used. The 22.8 million MT of recovery tailings at these 25 locations involving 1022 acres represents a formidable radon sealing problem.

Of these 25 sites, eight inactive tailings sites were sampled for analysis of physical and chemical characteristics that could adversely affect the formation of a radon-tight seal or the seal's long-term stability. Two of these, the Vitro site at Salt Lake City, Utah, and the Ambrosia Lake site at Grants, New Mexico, had been sampled in 1976 at the beginning of this project. The six sites sampled during 1978 were: Shiprock, New Mexico; Mexican Hat, Utah; Tuba City and Monument Valley, Arizona; Falls City, Texas; and Grand Junction, Colorado. These sites were selected primarily because of their potential as locations for a field test.

Initially, a minimum of three 5-gal samples were taken from each site. As it was determined which site was the most promising candidate for a field test, additional samples were taken. Currently, 50 samples have been taken from selected sites. Since the Grand Junction tailings site was selected for the field test, the majority of the characterization work was performed on Grand Junction tailings.

Sampling locations on each site were selected to cover the wide range of materials found at these sites including slimes, overburden, dike materials, and various tailings.

TABLE 1. Location, Quantity and General Mill Process for 25 Inactive Uranium Mill Tailings Sites

State and Site	Years Operated	Tailings, 1000 MT	Radium, Ci	Tailings Acres	Recovery Process
Arizona					
Monument Valley	1955-1967	998	50	10	Acid (Heap)
Tuba City	1956-1966	726	670	22	Acid/Alkaline
Colorado					
Durango	1943-1963	1,420	1,200	21	Alkaline Acid w/HCl
Grand Junction	1951-1970	1.730	1,350	59	Acid with HCl
Gunnison	1958-1962	490	200	39	Acid
Maybell	1956-1964	2,360	640	80	Acid
Naturita[(a)]	1939-1963	635	490	23	Alkaline/Acid
New Rifle	1958-1972	2,450	2,130	32	Acid
Old Rifle	1924-1958	317	320	13	Acid with HCl
Slick Rock (NC)	1931-1943	34	30	6	Acid
Slick Rock (UCC)	1957-1961	317	70	19	Acid
Idaho					
Lowman	1955-1960	82	10	18	-
New Mexico					
Ambrosia Lake	1958-1963	2,360	1,520	105	Alkaline
Shiprock	1954-1968	1,500	950	72	Acid
North Dakota					
Belfield	1964-1968	-	-	23.5	Burning lignite
Bowman	1964-1967	-	-	21	Burning lignite
Oregon					
Lakeview	1958-1960	118	50	30	Acid
Pennsylvania					
Canonsburg	1911-1942	∿180	-	19	-
Texas					
Falls City	1961-1973	2,270	1,020	146	Acid
Utah					
Green River	1958-1961	11	20	9	Acid
Mexican Hat	1957-1966	2,000	1,560	68	Acid
Salt Lake City	1951-1968	1,700	1,380	111	Acid
Wyoming					
Baggs		10	-	0.4	
Converse County	1962-1965	170	60	5	Acid
Riverton	1959-1963	816	500	72	Alkaline/Acid
TOTALS		22,775	14,220	1,023.9	

(a) Tailings have been removed and reprocessed for uranium.

PROPERTIES OF TAILINGS

Selected samples gathered from each site were analyzed to determine their chemical and physical characteristics. Tables 2 and 3 show some characteristics of the tailings samples, including particle size, moisture content, and pH.

The particle size analyses were made to pinpoint high-surface-area materials like silts, clays or slimes such as in Grand Junction sample, 2A.

TABLE 2. Characteristics of Selected Uranium Mill Tailings Samples

Site	Prior Processing	pH H_2O	% H_2O Content	Sample Appearance
Grand Junction, Colorado				
GJ - 1	acid leach	7.0	7.2	sand
GJ - 2	-	6.2	2.0	sand
GJ - 3	-	7.8	6.1	sand
GJ - 4	-	8.1	5.7	sand
GJ - 5	-	6.4	5.0	sand
GJ - 6	-	5.3	2.1	sand
GJ - 7	-	8.1	3.0	sand
Average		7.0	4.4	
Shiprock, New Mexico	acid leach	3.3	--	sandy, containing 3-in. to 8-in. rock
Falls City, Texas	acid leach	3.1	--	slimes, sand and clay composite
Tuba City, Arizona	acid & carbonate leach	2.7	--	high clay content - very fine
Mexican Hat, Utah	acid leach	5.0	--	sand, slimes composite
Monument Valley, Arizona	acid	5.5	--	coarse sand, slime composite
Vitro, Utah	acid	3.5	--	sand, sludge, slimes, composite
Ambrosia Lake, New Mexico	carbonate	9.1	--	fine sand, clay

TABLE 3. Particle Size Distribution of Selected Uranium Mill Tailings Samples

Screen Size, Tyler Mesh	Shiprock[a] SR-1	Monument[a] Valley MV-1	Tuba[a] City TC-3	Grand Junction[b] 8-A	7-D	6-C	5-B	2-A
	Sample Cumulative % Passing							
8	-	-	-	99.7	00.7	99.9	99.9	98.5
10	96.4	97.0	97.7					
14	94.7	94.1	96.1	99.4	99.0	98.8	994	96.9
20	93.1	88.4	93.9					
28	91.4	77.4	91.5	98.6	97.8	99.0	97.2	95.0
35	89.8	59.1	88.5					
48	83.3	37.2	85.5	86.6	86.4	93.5	84.3	87.7
65	66.4	18.5	81.5					
100	40.5	7.7	69.6	41.1	44.5	33.6	40.7	62.8
150	24.1	3.4	46.8					
200	12.2	1.3	18.9	10.2	16.8	7.3	11.4	38.9
270	7.8	0.7	9.9					
400	4.7	0.4	7.5					

(a) Samples were dry-screened.
(b) These Grand Junction samples were taken in the field test site. All the Grand Junction samples were wet-screened.

Clay-like materials agglomerate and are therefore coated by cationic asphalt emulsion in agglomerated lumps as opposed to sands where each particle is coated. Coated clay agglomerates could fracture under mechanical force, providing radon pathways. Particles of a very narrow size range as exhibited by the Grand Junction tailings could be difficult to compact. Subseal compaction is therefore required for seal stability.

The soil moisture content and pH analyses indicate those tailings for which asphalt emulsion bonding might be a problem. Soils containing less than 8 wt% water will remove water from the asphalt emulsion, which will concentrate the emulsified asphalt, causing the asphalt to agglomerate without bonding to the soil. Diluting the emulsion with water solves this problem, but increases the time between application and compaction of the seal because the added water must evaporate before compaction.

The pH value of a tailings sample indicates the acid-base environment in which the asphalt emulsion must operate to form gas-tight bonds to the aggregate. Emulsion selection is guided in part by pH as some emulsions are unstable in acidic media; other emulsions are unstable in alkaline media. If salts are present in the sample as in the case with tailings samples, the pH value is depressed on the average of one pH unit according to American Society of Agronomy (ASA).(4) To overcome pH measurement variability due to salts, the pH is measured using 0.01$\underline{M}$ $CaCl_2$ solution in place of distilled water. The pH value was found to be stabilized at 0.5 pH, a unit below that obtained in distilled water. Sample salt content variability did not influence pH measurement in 0.01$\underline{M}$ $CaCl_2$ solution. Dissolved atmospheric CO_2 could only influence pH measurements of samples whose pH was above 6.5.

In general the tailings are not uniformly deposited because of changes in milling processes, ore sources, and migration of slimes. Also a variety of materials was discarded into the tailings such as piping, rocks, concrete, etc. This, together with the previously mentioned characteristics, could have a direct effect on any sealing process.

In order to characterize the chemical nature of the tailings, x-ray fluorescence (XRF) (Table 4), neutron activation (Table 5), and radionuclide measurements (Table 6) were performed on selected tailings samples. We were concerned with identifying any elements that would be detrimental to the asphalt emulsion seal, and we were concerned with locating areas of high radium content.

ASPHALT SEAL FORMULATION

It was apparent from previous testing that a simple poured-on or sprayed-on seal would not be able to withstand mechanical forces involved in overburden installation. Overburden is required for protection from ultra violet radiation, oxygen/ozone, wind and water erosion, and animal/root intrusion.

TABLE 4. X-Ray Fluorescence Analysis of Grand Junction Tailings Samples[a]

Sample[b]	P%	S%	K%	Ca%	Ti%	Fe%	V	Cr	Mn	Ni	Cu	Zn	Ga	Hg	Se	Pb	As	Br	Rb	Sr	Y	Zr	Nb	Mo	U
GJ-1	0.56	2.5	1.40	3.1	0.24	1.8	2417	74.9	102	190	42.4	120	10.0	4.6	47	174	246	2.2	40	188	16.7	145	6.3	17.0	114
GJ-2	0.48	1.4	1.30	1.9	0.17	1.1	1477	43.1	109	50	12.5	130	7.3	3.7	62	78	60	1.7	45	106	9.9	159	6.3	11.0	40
GJ-3	0.50	0.9	2.30	2.8	0.35	2.7	386	86.5	295	50	36.7	145	19.3	4.2	7	56	32	3.7	122	173	32.3	178	13.1	4.0	20
GJ-4	0.48	0.2	2.50	2.4	0.37	2.8	222	74.5	294	35	24.6	117	18.1	3.9	3	36	13	4.3	136	165	27.1	197	13.7	3.6	6
GJ-5	0.50	1.4	0.67	1.7	0.12	1.1	2501	54.3	51	159	23.7	106	5.8	10.9	50	142	206	2.2	20	125	7.8	224	4.8	16.9	172
GJ-6	0.51	0.8	0.47	0.6	0.06	0.2	1694	14.5	12	30	10.4	125	3.0	3.7	78	97	35	1.0	12	61	3.0	131	2.9	22.4	91
GJ-7	0.50	0.4	2.10	3.7	0.29	2.2	446	45.7	222	11	22.3	113	14.2	3.8	9	35	17	3.4	94	185	12.1	205	11.1	5.2	24
Ave.	0.50	1.1	1.53	2.5	0.23	1.9	1306	57.6	155	77	24.7	122	11.1	4.9	38	90	87	2.6	67	144	16.9	177	8.3	11.4	67

(a) Parts per million (ppm) unless otherwise indicated.
(b) Taken from same composite samples as those which were screened in Table 3 and which were used for laboratory flux measurements as described later in this report.

TABLE 5. Neutron Activation Analysis of Selected Tailings Samples

Sample[a]	K%	Ca%	Fe%	Na%	Co	Cr	Br	As	Se	Ba	Sb	Sc	Rb	Cs	La	Ce	Ew	Tb	Yb	Lu	Hf	Ta	Th	U_2
Monument Valley MV-1[b]	0.21	0.2	0.32	0.008	12.8	8.4	14.7	21.5	1.9	800	0.3	0.6	6.1	--	44	56	0.4	0.27	1.1	0.18	6.0	0.24	4	33
Falls City FC-2[b]	1.7	2.3	0.26	1.8	1.1	3.4	4.8	15.0	5.9	800	0.5	1.1	49.0	--	12	12	0.6	0.17	0.7	0.15	1.9	0.4	3	51
Shiprock SR-1[b]	0.9	0.7	0.3	0.1	2.9	52	110	24.0	20.0	940	1.3	1.2	1.3	0.3	6.9	4.5	0.3	0.2	1.7	0.30	4.1	0.2	3	58
Mexican Hat MH-4[b]	0.5	16.0	2.5	0.2	10	13	14	400	--	230	0.6	2.8	13	--	16	46	2.7	1.5	1.3	0.24	0.6	0.1	330	31
Tuba City TC-3[b]	1.1	2.2	1.0	0.1	53	22	200	930	1.6	1430	4.9	1.2	30	0.3	7.2	--	0.3	0.16	0.7	0.10	4.0	0.3	2	103

(a) These are averages of duplicate samples.
(b) Parts per million (ppm) unless otherwise indicated.

TABLE 6. Radionuclide Contents of Selected Tailings Samples[a]

Sample	^{210}Pb	^{214}Pb	^{226}Ra	^{230}Th	^{235}U
Grand Junction					
GJ-1	664	628	1036	930	2.4
GJ-2	249	230	337	156	1.6
GJ-3	69	63	101	103	1.7
GJ-4	12	9	13	19	0.8
GJ-5	324	308	456	424	2.3
GJ-6	236	130	190	13	0.8
GJ-7	30	23	34	19	0.9
Monument Valley[b]					
MV-1	53	43	62	22	0.1
Falls City[b]					
FC-2	34	258	335	121	1.4
Mexican Hat[b]					
MH-4	575	109	144	1488	0.1
Tuba City[b]					
TC-3	495	580	608	318	1.4
Shiprock[b]					
SR-1	435	406	551	309	2.4

(a) All values are given in pCi/g.
(b) Analysis is average of duplicate samples.

Therefore, tests on admixtures of tailings and cationic asphalt emulsion, were initiated (Figure 3) to provide a thicker, more mechanically stable radon seal. Admixtures containing 10 to 20 wt% residual asphalt were prepared and tested to determine if a radon seal could be obtained with improved strength to resist animal and root penetrations as well as the pressures of equipment traffic during overburden installation.

FIGURE 3. Admixture Seal Test Sample

The admixtures first underwent standardized test procedures of the highway construction industry. The Marshall tests ASTM D1556-76, while designed to indicate stability of pavement admixtures under traffic load, give only some idea of the strength to be expected in the field for sealing the tailings. Other tests determined parameters necessary to select the optimum asphalt emulsion. Armak Highway Chemicals Laboratory, McCook, Illinois performed tests with mixtures up to the residual asphalt content (12 to 14 wt%) that was impermeable to water vapor. Further testing of actual seal impermeability to radon was performed at PNL facilities and is discussed in a subsequent section.

Three separate emulsifiers were investigated: Armak Redicote E-63, E-65, and E-4868. These emulsions were selected because of their low positive surface charge (zeta potential), which would provide maximum coverage of the particulates with minimal agglomeration. These emulsifiers are used in preparation of highway-grade asphalt emulsions which are categorized as CSS-1 emulsion, a cationic, slow-setting emulsion. Based on the particle size analysis and the calculated surface area of the tailings (3.8 m^2/g), E-4868 was selected as the best available emulsifier.

LABORATORY RADON DIFFUSION MEASUREMENTS

Radon diffusion measurements are performed in the laboratory to determine the effectiveness of various cationic asphalt emulsions in producing a radon seal. The following paragraphs detail the test apparatus and procedures used in our work to accomplish these measurements.

Two test setups were used for radon diffusion measurements. The first setup shown in Figure 4 was used to initially test the effectiveness of cationic asphalt emulsion seals on various tailings.

Each sample of tailings from the various sites was put in the test can, and a canister containing activated carbon was placed on the tailings surface. After several hours the canister was removed and the activated carbon was transferred to a 15.4-cm-dia Petri dish and sealed. The carbon is allowed at least 4 h to equilibrate before it is counted. Next the tailings surfaces were saturated with water and covered with enough asphalt emulsion to provide a 3- to 7-mm-thick seal. After each sample cured (~48 hr) a canister containing activated carbon was placed on the seal and then cemented to the surface. After the can had been in place for several days, it was removed and the activated carbon transferred to a plastic Petri dish and counted. From this data the pre-seal and post-seal radon fluxes were determined.

FIGURE 4. Experimental Test Setup for Static Radon Diffusion Measurements

The second and primary setup shown in Figure 5 was developed to obtain more accurate radon diffusion measurements and provide flexibility for testing a variety of seals. Photographs of the test apparatus are shown in Figures 6 and 7. This setup allows the bottom of the asphalt emulsion seal to be exposed to a high concentration of radon gas at an elevated pressure, such as 0.1 to 0.3 psi. A 120 mCi, $^{226}RaCl_2$ source continously sprayed with 150 cc/min nitrogen provides a constant 15 $\mu Ci\,^{222}Rn/min$ source. Details on the radon source have been presented in reference 2. Another advantage of the system is that various nitrogen/radon gas pressures can be applied to the bottom of the seal by restricting the exit flow, simulating various sealed tailings pile conditions.

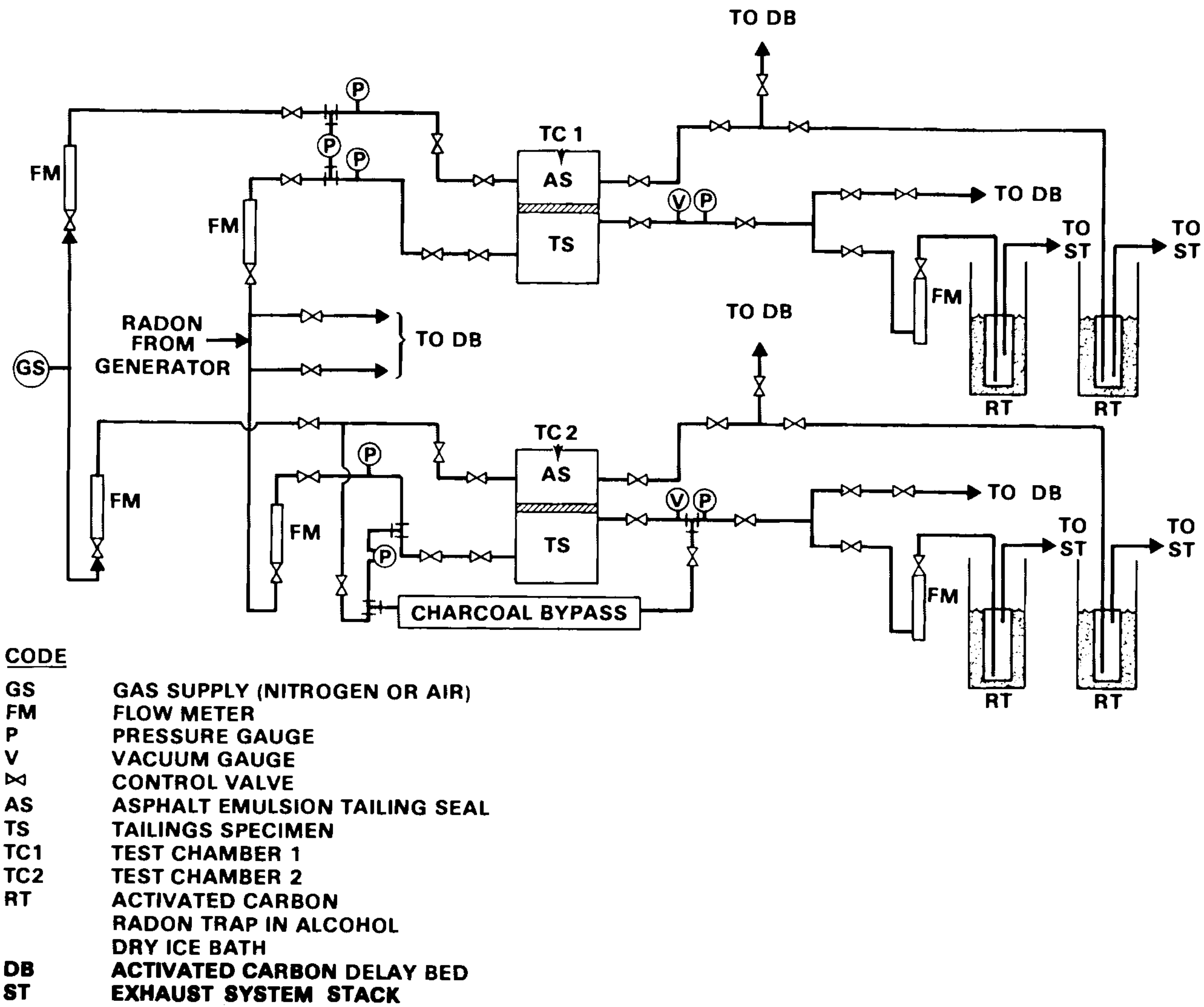

FIGURE 5. Basic Experimental Setup for Asphalt Emulsion-Tailings Seal Radon Diffusion Measurements

FIGURE 6. Overall View of Basic Experimental Apparatus for Primary Radon Diffusion Measurements

FIGURE 7. Radon Diffusion Test Cells in Operation

The top of the seal is swept continuously by nitrogen gas to pick up any radon diffusing through the seal. Any radon that diffuses through the seal is adsorbed on activated carbon maintained at -78^{o}C by using a dry ice/alcohol bath which improves its collection efficiency to greater than 99%. These radon diffusion measurement tests are usually run for up to two weeks unless a major leak occurs.

Two sealing procedures are tested using the plexiglas radon diffusion test chamber shown in Figure 8. The first procedure consists of placing tailings in the chamber, compacting them, saturating the surface with water, and pouring on cationic asphalt emulsion until a 3- to 6-mm-thick seal is achieved. The second procedure consists of preparing an admix seal by mixing cationic asphalt emulsion directly with the tailings in a laboratory mixer and compacting this admixture (Figure 9). The compacted seal is then placed on sand in the test chamber, sealed to the sides of the chamber with asphalt cement, and then tested.

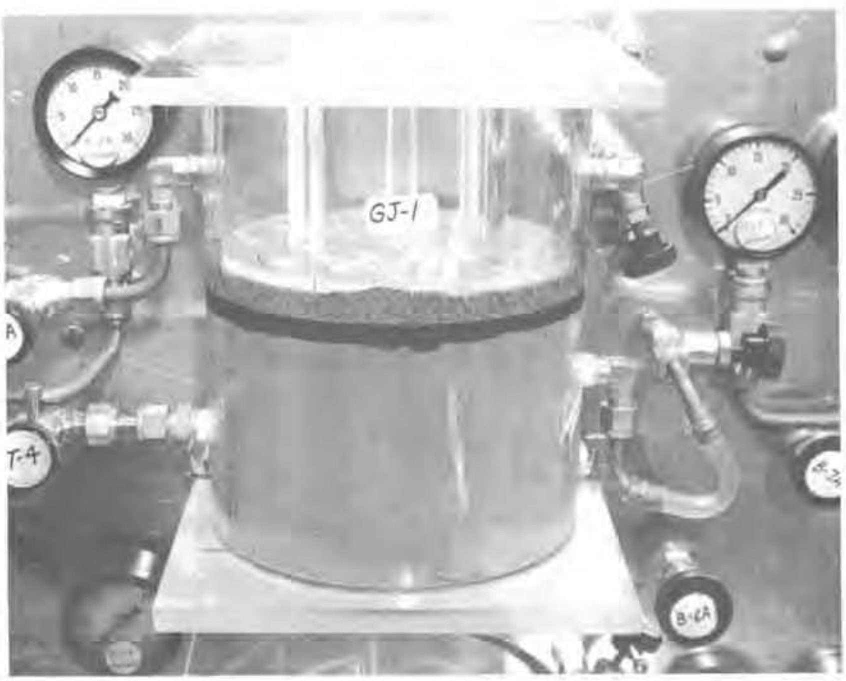

FIGURE 8. Radon Diffusion Test Chamber

FIGURE 9. Asphalt Emulsion-Tailings Admix Seal Compaction

Radon Flux Measurements Using Activated Carbon

Activated carbon is an accepted collector for radon gas. Exhaled radon is accumulated by adsorption on activated carbon and quantified by gamma-ray spectrometric analyses. U.S. military gas canisters, commercial canisters, and home-made canisters have been used for radon flux measurements.[5,6,7,8] This method has been reported to provide measurements of radon fluxes with an accuracy and precision of $\pm 15\%$. Immersion of carbon canisters in a dry ice/alcohol bath to lower the carbon to $\sim -78^{\circ}C$ is recognized as a more effective means of trapping radon gas from a flowing gas.[4] Our measurement systems incorporate the use of activated carbon in a dry ice/alcohol bath.

Radon Collection Systems

Both static and dynamic radon collection systems are used in laboratory and field studies. A "static" carbon canister,[6] was used for preliminary laboratory tests as previously illustrated in Figure 2. In order to significantly improve the sensitivity of the collection system, a flow-through system using activated carbon in a canister cooled with a dry ice/alcohol bath was used for the primary radon diffusion measurements in both the laboratory and field studies (Figure 10). The flow-through system with -78°C collection temperatures is not as affected by atmospheric temperature and pressure changes as the static system.

FIGURE 10. Activated Carbon Canisters in Dry Ice/Alcohol Bath Used for Trapping Radon During Laboratory Tests

Counting System

After the radon measurement tests are complete, the cold carbon is transferred to 15.4-cm-dia x 2.5-cm polystyrene Petri dishes and tape-sealed. The Petri dish is double bagged to preclude contamination. As the carbon reaches room temperature, the radon uniformly disperses throughout the carbon, becoming adsorbed on all the carbon particulates and thus providing a reproducible counting geometry. Prior to counting, the carbon sample is stored a minimum of 4 h to allow the daughter products to reach near equilibrium with the parent radon. The radon (^{222}Rn) collected by the activated carbon is determined by counting the ^{214}Pb and ^{214}Bi daughter concentrations and accounting for the decay occurring during the delay before counting. Two systems are used for radon measurement, depending upon gamma radiation levels. A multidimensional gamma ray spectrometry system[9] with anticoincidence shields is utilized for low-activity radon samples. An intrinsic germanium diode system[10] is used for high-activity radon measurements. Sealed sources of identical geometry containing known amounts of ^{226}Ra in equilibrium with its daughters are used for system calibration and intercalibration of the two systems. Typical measurement error is less than 5% in both systems. In most cases the ^{214}Bi 0.609-MeV gamma energy is used for detection since it is relatively free from interfering radiation, at least compared to the gamma energy of ^{214}Pb.

The flux is determined from the data obtained from the counting equipment by using the following calculation:

$$J[\mathrm{pCi}/(\mathrm{cm}^2 \cdot \mathrm{s})] = \frac{C\lambda^2}{3.7 \times 10^{-2}\ (E)(A)(1-e^{-\lambda t'})(e^{-\lambda t'}-e^{-\lambda t''})}$$

where:

c = net counts

λ = radon decay constant (2.097×10^{-6}/s)

E = counting efficiency (counts/disintigration)

A = radon emanating area covered by measurement apparatus (cm^2)

t = exposure time (seconds)

t' = time between end of sampling and start of counting (seconds)

t'' = time between end of sampling and end of counting (seconds)

3.7×10^{-2} = conversion factor, dps/pCi

Results of Laboratory Radon Diffusion Measurements

Radon flux reductions by poured-on seals and admix seals are tabulated in Tables 7 and 8. Cationic asphalt emulsions prepared with Armak Co. Redicote E-63, E-65, and E-4868 emulsifiers were used to make the seals.

TABLE 7. Radon Flux Reduction Using Poured-On Asphalt Emulsion Seals and Static Test System

Sample	Asphalt Emulsion	pCi/(m^2·s) Control	pCi/(m^2·s) After Seal	% Reduction in Exhalation	Seal Thickness, mm
Vitro SS-101	E-65	80.0	8.7×10^{-3}	>99.9	3.2
Ambrosia Lake ALMM-14	E-65	70.0	8.7×10^{-3}	>99.9	4.8
Mexican Hat MH-4	E-65	4.3	3.2×10^{-2}	99.3	4.8
Monument Valley MV-1	E-65	5.4	8.7×10^{-3}	99.8	7.9
Shiprock SR-1	E-65	29	8.7×10^{-3}	>99.9	4.8
Tuba City TC-3	E-65	16	8.7×10^{-3}	>99.9	4.8
Falls City	E-15	15	8.7×10^{-3}	>99.9	4.8
FC-1	Auto Undercoat	5.8	1.5×10^{-2}	>99.9	4.8
	E-65	5.8	6.5×10^{-3}	>99.9	4.8
FC-2		7.5	8.7×10^{-7}	>99.9	6.4
Grand Junction					
GJ-1	E-65	154	8.7×10^{-3}	>99.9	9.5
GJ-2	E-65	45	8.7×10^{-3}	>99.9	12.8
GJ-3(TS)	E-65	22	2.6×10^{-2}	>99.9	9.5
GJ-4(TS)	E-65	1.6	8.7×10^{-3}	99.5	9.5
GJ-5	E-65	72	8.7×10^{-3}	>99.9	9.5
GJ-6	E-65	19	9.7×10^{-3}	99.7	10.0
GJ-7(TS)	E-65	2.8	1.4×10^{-2}	99.5	9.5

All flux reductions were greater than 99.3% with poured-on seals. However, poured-on seals are not adequate for field application since they do not have enough mechanical stability. Therefore, admixes of tailings and asphalt

TABLE 8. Radon Flux Reduction Using Poured-On and Admix Asphalt Emulsion Seals and Dynamic Test System

	Asphalt Emulsion	pCi/(m²·s) Below Seal	Above Seal	% Reduction in Exhalation	Seal Thickness, mm
Poured-on Seals					
Grand Junction					
GJ-1	E-65	6.7×10^6	2.6×10^3	99.96	7-10
GJ-3	E-65	1.3×10^6	3.7×10^3	99.94	7-10
GJ-5	E-65	1.0×10^6	1.3×10^3	99.87	7-10
GJ-6	E-65	6.8×10^6	3.4×10^2	99.99	7-10
Admix Seals					
Residual Asphalt Content, wt%					
13.5	4868	--	--	Seal Failed	~7.6 cm
15	4868	--	--	~50%	~7.6 cm
18-20	4868	2.3×10^9	6.2×10^4	>99.99%	~7.6 cm

emulsion were tested using the pressurized radon diffusion test apparatus. Admixes containing from 10 to 20 wt% residual asphalt were compacted at about 5.6 kg/cm^2 (80 psi) and tested. Admixes containing 10 to 12 wt% residual asphalt stopped neither water vapor nor radon. Admixes containing 12 to 14 wt% residual asphalt sealed out only water vapor. Starting at a residual asphalt content of 14-wt%, a marked reduction in radon flux was noted (~50%). At an 18 to 20 wt% residual asphalt, a greater than 99.9% reduction in radon flux was obtained, even when a nitrogen/radon pressure up to 0.3 psi was applied to the seal. Pressure was applied to simulate any potential pressure buildup that might occur when an actual tailings pile is sealed. Based on these laboratory results, it was concluded that an 18 to 20 wt% residual asphalt emulsion seal would be used for the field test at Grand Junction. The Armak E-4868 cationic asphalt emulsion was selected for the field test because of its mixing and sealing characteristics when using the fine Grand Junction tailings. Other emulsions tested such as Armak E-63 and E-65 did not coat or mix as well.

FIELD STUDIES

The overall objective of the field studies is to demonstrate the effectiveness of stabilization or sealing procedures using asphalt emulsion to contain radon. Techniques for applying the asphalt emulsion seal are being investigated at selected tailings sites. The objectives of the field tests are to obtain sufficient data to evaluate the technical and economic feasibility of the most promising application techniques.

APPLICATION TECHNOLOGY

One objective of the field studies is to identify and/or develop a cost effective and reliable procedure for applying a radon seal over uranium mill tailings. The procedure chosen consists of 1) mixing uranium tailings with cationic asphalt emulsion to form an admixture, 2) compacting the admix over the remaining tailings to form the gas-tight seals, and 3) applying a spray-coat emulsion seal over the admix to fill microcracks. This procedure was arrived at by:

1) examining asphalt/asphalt emulsion standard paving practice
2) discussing the sealing problem with various representatives of the paving industry
3) observing commercial equipment in operation
4) reviewing PNL laboratory test results.

These four steps led to the following criteria for evaluation of the available application equipment as to its suitability for our purposes. The application process must: 1) deliver a mechanically stable and radon-tight seal, capable of supporting the application equipment and a minimum of 2 ft of overburden; 2) be accomplished with commercially available equipment; and 3) be as cost effective as possible.

This examination quickly narrowed to two considerations: The equipment needed to properly compact the seal base (tailings) and the equipment needed to apply or make the seal. As the equipment used to make the seal would determine the extent of base preparation required, the sealing equipment was determined first.

The examination of current practices revealed three options. The first option was to spray a thin coat of asphalt emulsion onto the tailings using a distributor truck. Even though this option would stop radon exhalation, it fails to meet the other criteria except for cost. It is the least expensive technique of the three options. Unfortunately the seal, would be susceptible to easy puncture and would probably not support any overburden.

The second option involves placing a 7.6-cm (3-in.) compacted admixture of asphalt emulsion/with tailings or sand on the tailings surface using standard paving procedures including substantial base preparation, aggregate transport, and aggregate/asphalt emulsion mixing in a pug mill at asphalt concentrations much higher than normally encountered in highway applications. This type of procedure, although probably capable of applying the seal, appeared to be complex and costly.

Use of tailings themselves as the aggregate source could potentially reduce aggregrate cost; however, classification of the tailings would probably be required to remove fines ($\sim$200 mesh material).

Mixing the asphalt emulsion with aggregate in a pug mill with 18 to 20 wt% residual asphalt emulsion has not been tried. This could be an alternative to the other two options and should be further evaluated for future considerations.

The third option is a compromise of the other two. This option involves mixing the tailings with asphalt emulsion in place, using standard pavement-base preparation equipment (soil stabilizer) to form an admix seal. No aggregate transportation is contemplated other than site contouring. The 7.0- to 15.2-cm (3- to 6-in.) seal obtained should provide the necessary mechanical stability. These potential advantages prompted us to try to develop an asphalt emulsion seal using a hydrostatic soil stabilizer. The BOMAG MPH 100 hydrostatic stabilizer (Figure 11) was selected for the initial field test after observing its operating characteristics.

FIGURE 11. BOMAG MPH 100 Hydrostatic Stabilizer

Once the sealing equipment was selected, the criteria for tailings and admix seal compaction were determined. Base preparation requires a deep lift;[a] a greater than 15.2-cm (6-in.) depth of compaction. This requirement was also tempered with the knowledge that the narrow-size-range sand we would be working with would be difficult to compact. With this in mind, we also required equipment that would accomplish the required compaction in as few passes as possible, again, striving for any cost benefits. Compaction of the seal itself, while not requiring a deep lift, does call for an end product with a minimum of void space.

Our examination of current compaction practices revealed two options. The first option, involved using a static roller train such as a sheeps foot or steel-style roller for the base compaction, in conjunction with a rubber-tired/steel-wheeled roller pair for the seal compaction.

This option fared poorly with our criteria. Standard practice accepts 9 to 10 passes as necessary to provide acceptable densities. Whether or not static rolling would deliver the needed lift thickness was open to question.

(a) Lift is the depth of a material (in this case either tailings or admix) which has been compacted to a specified percentage of maximum density.

The need for two, perhaps three separate pieces of equipment raised compaction costs considerably. We therefore looked for other options.

The second option called for the use of a vibratory compactor. Advocates claim compaction lifts of greater than 25.4 cm in 4 passes or less. These advantages singled out vibratory compaction for our use.

Contacts with Koehring's BOMAG division, a compaction and general equipment manufacturer, enabled us to have their MPH 100 hydrostatic stabilizer and BW220A tandem vibratory compactor available for our use during the field test.

SITE SELECTION

The Grand Junction tailings site (see Figure 12) was selected as the field study site because both equipment and materials needed for the study were readily available in Grand Junction. Many necessary tools, chemicals, etc. were locally available. Also, very little site preparation was needed since the tailings pile was relatively level. In addition, Department of Energy facilities and equipment were available at the Grand Junction DOE office.

FIGURE 12. Grand Junction Tailings Site

The specific field test area selected at the Grand Junction tailings pile is shown in Figure 13. The northwest end of the pile was quite level in comparison to the rest of the pile. Access roads to this end of the pile were already present. This led to the decision to locate the test site at the northwest end of the pile.

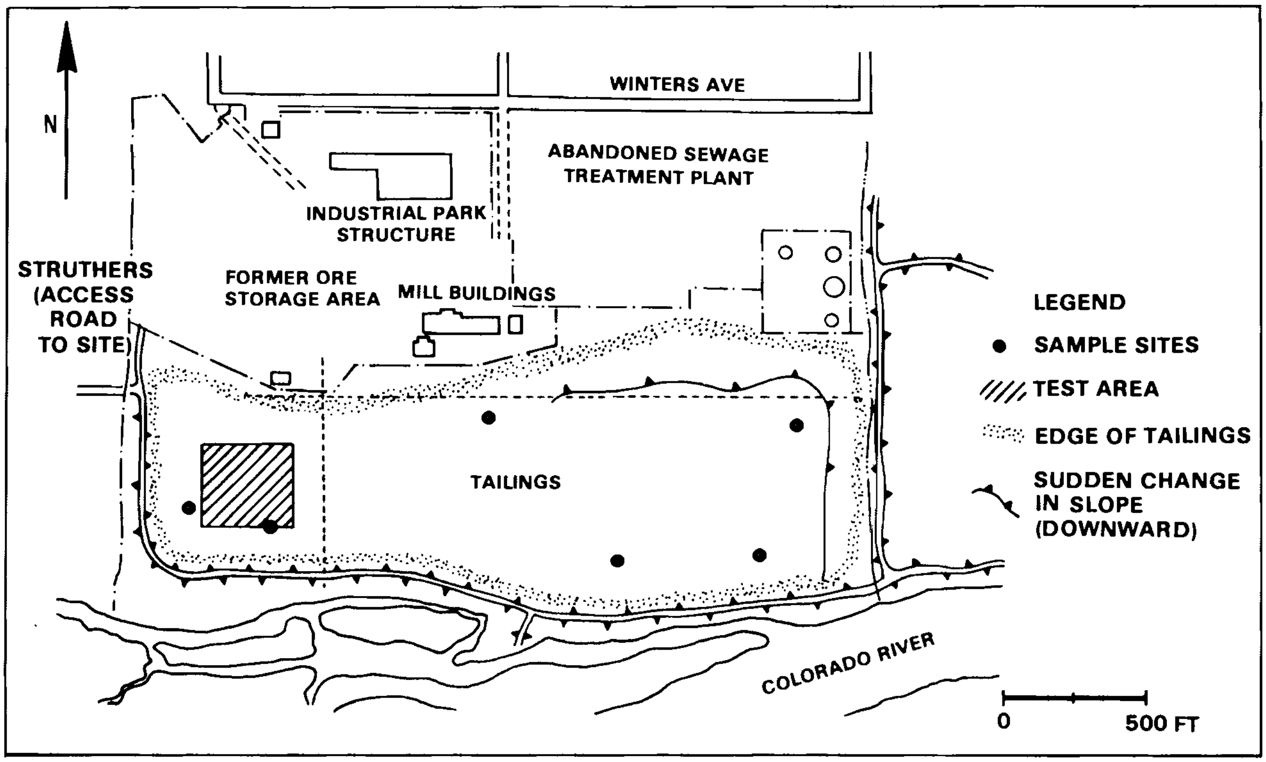

FIGURE 13. Grand Junction Field Test Area

SEALING PROCEDURE FOR GRAND JUNCTION FIELD TEST (June 1979)

The stabilization/sealing procedure selected for the initial field test at the Grand Junction tailings site consisted of 1) site preparation (contouring, watering, compaction), 2) seal application using a soil stabilizer to apply the asphalt emulsion admix seal followed by compaction and spray top coat to form the seal, and 3) overburden application as illustrated in Figure 14.

In order to obtain the data necessary to accomplish the basic field test objectives, the following principal activities were to be carried out during the field test.

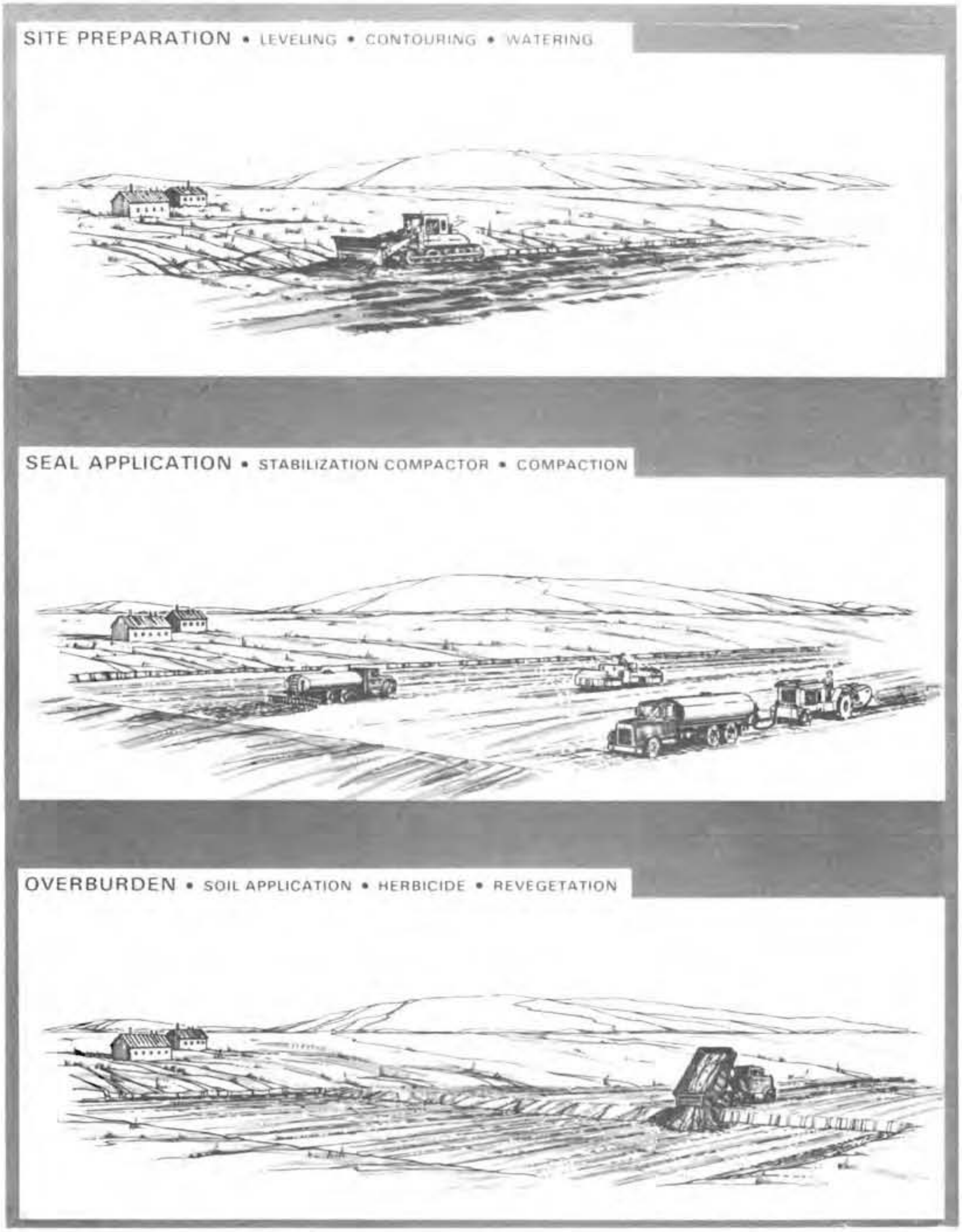

FIGURE 14. Asphalt Emulsion Sealing Procedure

- Test the basic stabilization/sealing procedure to produce a mechanically stable seal.
- Demonstrate the ability of a soil stabilizer to apply cationic asphalt emulsion to the tailings.
- Demonstrate the ability of a vibratory roller to compact the asphalt emulsion-tailings mixture to produce a radon seal.
- Observe the effect of site preparation on equipment operation and seal integrity.
- Determine seal integrity by periodic inspection of the asphalt emulsion seal.
- Determine the effectiveness of overburden in protecting the seal against mechanical abuse and weathering.
- Determine if root penetration will be a problem. (Herbicide was applied over part of the sealed layer.)
- Determine effectiveness of the asphalt emulsion seal (reduction of radon exhalation).
- Determine equipment operating parameters, e.g., emulsion application rate and seal thickness, in order to determine materials requirements and application capacity. Determine the pertinent physical properties of the seal.
- Observe degradation of thin asphalt emulsion top coat when exposed to UV-oxygen compared to buried top coat.

Using the experimental data, the technical and economic feasibility of the initial asphalt emulsion sealing procedure is evaluated later in this report. Also R&D required to commercialize the sealing procedure will be defined.

SITE PREPARATION

Before the asphalt emulsion could be applied, the tailings site had to undergo some preparation to provide a suitable surface for seal application.

First, sections of three 7.5-cm- (3-in.-) dia irrigation pipe lines had to be removed. (See Figure 15). They were taken beyond the east end on the field test site for storage until testing was complete; they were replaced after the testing. Next, a 83.8-m x 83.8-m (275-ft x 275-ft) test area was surveyed and staked at each corner.

The next major objective was to remove the 10 to 20 cm (4 to 8 in.) of overburden in order to expose the tailings. This was done because the overburden had a high clay content which made it unsuitable for sealing with asphalt emulsion.

Attempts to remove overburden by a grader or loader failed due to inadequate depth control. A paddle wheel earth mover (see Figure 16) was used to effectively remove the overburden because it controlled the depth of overburden removal. After overburden removal, a grader was used to smooth the tailing surface. The site was then contoured with the paddle wheel and grader to provide drainage to the northeast corner of the test site. A drainage ditch was cut with the paddle wheeler at the northeast corner of the site.

After the site was contoured, individual test plots, 41.9 m x 21 m (137.5 ft x 68.8 ft), were surveyed and staked out. Location of these test plots are shown in Figure 17. Radon flux measurements were made within each

FIGURE 15. Irrigation Pipes Needed to be Removed

FIGURE 16. Paddle Wheel Earth Mover Removing Overburden

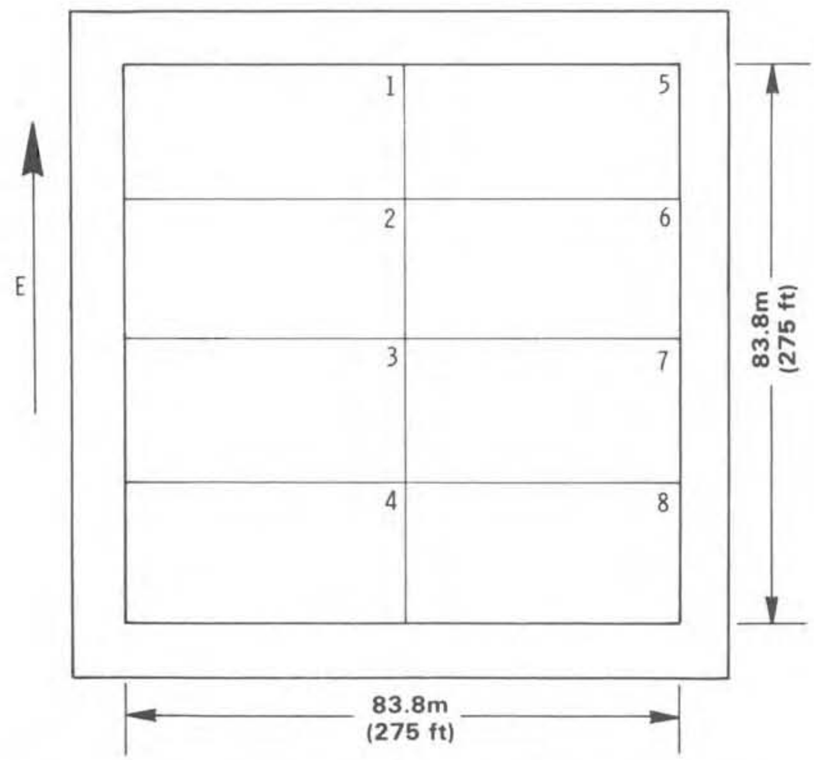

FIGURE 17. Overall Test Plot at Grand Junction Tailings Site

of the surveyed test plots in order to determine the radon flux from the bare tailings. This data is discussed in a forthcoming section.

SEAL APPLICATION

Before the admix seal was applied to the test plot, preliminary tests were run outside the test area to determine what quantity of asphalt emulsion should be used and what procedure for application should be used. These preliminary tests are described here, followed by a discussion of the main application tests.

Preliminary Application Tests

The preliminary test area was located at the east end of the overall test plot. The area had a considerable number of large rocks which would not provide for a good seal and had to be removed. To do this, the BOMAG MPH 100 was run through the area to fluff up the tailings and loosen the rocks. A rock picker was then used to remove the rocks. Once most of the rocks were removed, the area was backbladed with a tractor and then watered.

For the first application of asphalt emulsion, an 18 wt% residual asphalt, one-pass, admix seal was attempted. The BOMAG MPH 100 connected to the distributor truck was operated at 6.1 m/min (20 ft/min). Poor traction caused the rear wheels to dig into the tailings, resulting in much deeper penetration of the blades into the tailings than planned. After approximately 15.2 m (50 ft), this pass was stopped and then continued at a rate of 12.2 m/min (40 ft/min) (see Figure 18). The MPH 100 continued to bog down somewhat due to the fact that the MHP 100 was pushing the distributor truck, which did not have good traction in the fluffed tailings. The admix was compacted with a BOMAG vibrator compactor (see Figure 19) about 4 h after the admix was applied.

Examination of the seal the next day showed that the admix seal had set up very hard. However, due to the problems with putting down the admix seal at slow rates and with pushing the distributor truck, this method was determined to be unsuitable for use on the main test plot.

For the second preliminary test the distributor truck was hooked in tandem with the MPH 100, offset to the side, and traveled under its own power (see Figure 20).

FIGURE 18. Preliminary Test of BOMAG MPH 100 Applying Asphalt Emulsion

FIGURE 19. BOMAG 220A Vibratory Compactor

FIGURE 20. BOMAG MPH 100 and Distributor Truck Operating in Tandem

Also, instead of applying 16 to 18 wt% residual asphalt in one pass, a series of passes was made to achieve the 16 to 18 wt% residual. The first pass, ~9 wt%, was made and allowed to set. Close inspection indicated inadequate mixing of the tailings and emulsion; the MPH 100 went back over it without applying any more emulsion and remixed it. A second application of ~9 wt% residual asphalt was then applied, and subsequently remixed as before. After a several-hour wait to allow the water to separate, the strip was compacted with the vibrating compactor and allowed to set. A suitable admix seal was obtained with this procedure, so it was chosen as the one to use for the main test plot.

Main Application Tests

Preparation of the main test plot for the application of the admix seal consisted of several steps. First, the area was watered to aid in the compaction of the tailings. The area was then compacted with the 18-ton tractor since its large wheels provided kneading action which compacted the tailings better than the vibrator compactor. Water was added in an attempt to raise the tailings moisture content to about 8 wt%.

The first emulsion application was applied to an area of 3513 m^2 (4201 yd^2) at a rate of approximately 18.2 L/m^2 (4.0 gal/yd^2) with the BOMAG MPH 100 traveling an average speed of 11.7 m/min (38.5 ft/min). The depth control was set at 12.7 cm (5 in.) uncompacted admix. Poor mixing resulted as seen in Figure 21. Therefore, the MPH 100 went over the area after the first emulsion was applied and remixed the admix. This resulted in the admix looking much more uniform in composition. However, close observation revealed many particles that were not coated by the first emulsion application and subsequent remixing. Once it was remixed, it was allowed to stand for several hours and then was compacted with the BOMAG vibrating compactor.

The only operational problem encountered during the first emulsion application was when the distributor truck bogged down in the fluffed tailings at the east end of the plot. When this happened, the truck was towed with a tractor. Bogging down of the distributor truck did not occur during the second asphalt emulsion application because the compacted admix seal provided a firm base for the truck to drive on.

FIGURE 21. Results of Single-Pass, ~9 wt% Asphalt Emulsion Application - Poor Mixing

The next day, the second application of emulsion was applied (see Figure 22). The MPH 100 mixing depth was set at ~7.6 cm (3 in.) in depth. Once again poor mixing was observed during the application. Therefore the admix was remixed. The tailings looked much more uniform in composition after the second mixing. However, uncoated agglomerates of tailings were observed in the admix. These agglomerates are thought to be a result of the design of the mixing blades on the MPH 100 since they were designed to cut pavement instead of mixing tailings.

The admix was then compacted several times with the BOMAG vibratory compactor. An attempt to compact the admix transversly resulted in formation of cracks. The remainder of the compacting was done in the direction the mixture was laid down. Also, compaction resulted in a slight wave in the surface of the seal. This wave is thought to be due to the admix being pushed in front of the compactor because of poor tailings base stability.

In addition to the application test described above, an area about 815 m^2 (33.8 m x 24.1 m) (111 ft x 79 ft) in the northeast corner of the overall test plot was sealed using a slightly different procedure. Asphalt emulsion was applied in one pass instead of the two-pass system described previously. The

FIGURE 22. Second Application of ~9 wt% Asphalt Emulsion

average asphalt emulsion application rate was 36.3 L/m^2 (8 gal/yd^2). During this application, the MPH 100 was pumping the emulsion at maximum capacity, but a crimp in the hose between the distributor truck and the MPH 100 made it necessary to reduce the speed of the BOMAG to less than 12.2 m/min (40 ft/min) in order to apply 36.3 L/m^2. If it were not for the crimp in the hose, the MPH 100 could have applied 36.3 L/m^2 at 12.2 m/min. After the asphalt emulsion was applied, the admix was compacted with the BOMAG vibrating compactor about 6 times.

The next step in the tailings sealing procedure was the application of the spray-coat asphalt emulsion seal (see Figure 23). For the emulsion to penetrate the admix and bond well, the admix must be watered beforehand. However, when we were ready to apply the spray-coat seal, the water truck pump failed and we were not able to obtain a suitable substitute since it was on a weekend. The spray-coat seal was applied anyway, and a poor bond to the admix resulted. We could not wait until Monday because the admix seal would have been too cured for the spray-coat seal to bond. The sprayed-on asphalt emulsion was mechanically bonded to the compacted admix rather than electrostatically bonded. Therefore, the mechanical strength of the spray-coat seal was quite poor.

FIGURE 23. Applying the Spray-Coat Seal on the Admix Seal

Most of the test area in the northeast corner was also spray-coat sealed at the same time as the main test plot. It suffered the same lack of water as the main test plot. Also a region of base tailings between the northeast test plot and the southeast test was directly spray-coat sealed. As can be seen in Figure 23, the area where the distributor truck drove over the admix seal had tire track depressions. These depressions create areas in the seal that are more difficult to seal gas tight.

After several days, bubbles in the spray coat formed because of water vapor passing through the admix and expanding as a result of the high ambient temperatures up to 32°C (90°F) (Figure 24). This illustrates the poor bonding of the sprayed-on coating to the admix. These bubbles, if ruptured, are potential points for radon gas leaks.

The spray-coat-sealed major test plot is shown in Figure 25.

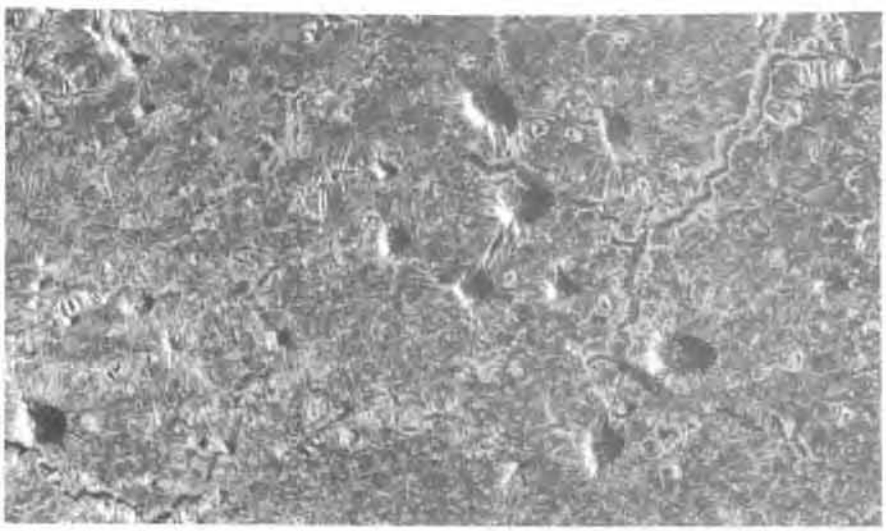

FIGURE 24. Bubbles in the Spray-Coat Seal Caused by Water Vapor from the Curing Admix Seal

FIGURE 25. Spray-Coat-Sealed Major Test Plot

OVERBURDEN APPLICATION

The objective of the overburden application was to provide a protective cover over the asphalt emulsion seal. The cover/overburden depth must be deep enough to protect the seal from mechanical abuse as well as weathering. For this initial field test about two-thirds of the exposed seal was covered with 20 to 30 cm (8 to 12 in.) of soil overburden as shown in Figure 26.

Also included in part of the test plot was the addition of a herbicide, Treflan®, to prevent root penetration. Treflan® was selected because of its ability to inhibit root growth rather than destroy the plant as most herbicides do. It was applied (Figure 27) after about 7.6 to 15.2 cm (3 to 6 in.) overburden was applied to the test area. Care was taken to prevent the overburden spreading equipment from breeching the admix spray-coat seal. Even with this care some breeching of the spray-coat seal occurred.

After the Treflan® was sprayed on the thin overburden layer, additional overburden was applied to bring the depth to about 25 to 30 cm (10 to 12 in.). The results of the Treflan® addition will not be available for about 1 yr from field test. At that time root penetration will be investigated.

FIGURE 26. Overburden on Seal

FIGURE 27. Herbicide (Treflan®) being applied to ~7.6 cm of Overburden on the Seal

ADMIX SEAL ANALYSIS

In order to determine if the admix seal applied in the field was of the composition expected, core samples of the admix seal were taken and analyzed by an independent testing laboratory in Grand Junction. See Figure 28 for sampling locations. The laboratory encountered considerable problems in obtaining the core samples using standard paving industry testing procedures. The reasons for this difficulty is threefold. First of all, the asphalt seal had not completely cured at the time of sampling. Therefore, the cores were not very strong and could not withstand the shearing action of the coring device. Secondly, the seal contained a much higher asphalt content than is encountered in the paving industry, which further added to the weakness of the seal cores. Lastly, the seal was poorly mixed and compacted, which even

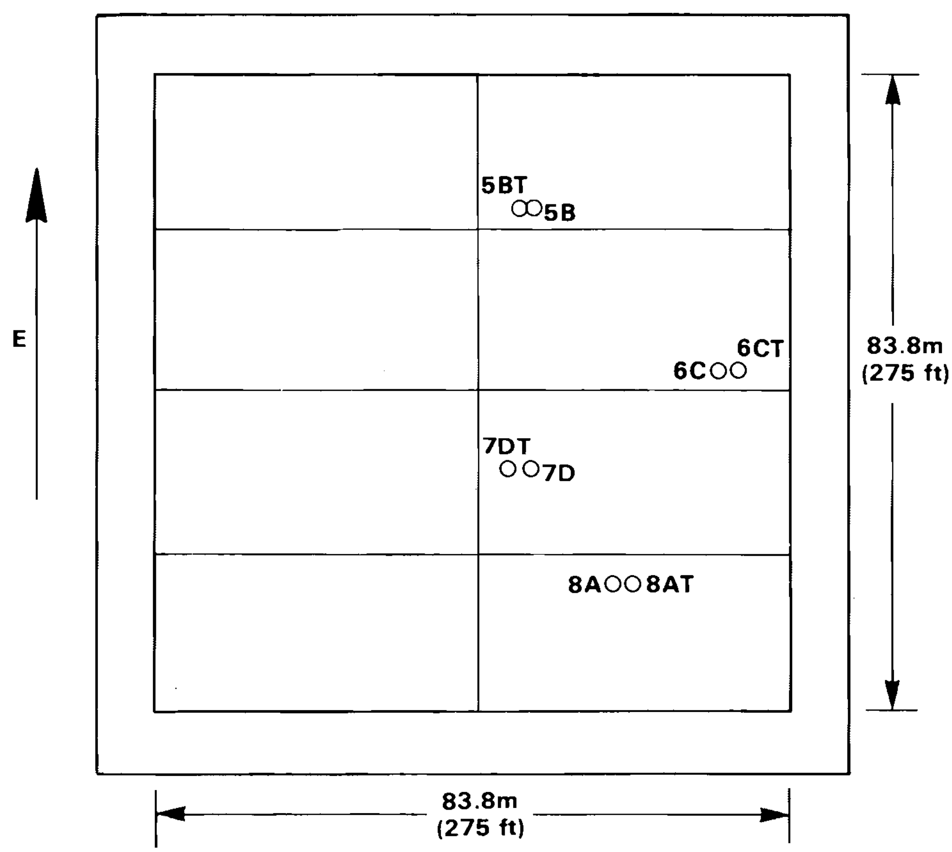

FIGURE 28. Approximate Locations where Seal Core Samples were Taken on the Grand Junction Tailings Site

further reduced the mechanical strength of the seal. However, the laboratory was able to obtain nine core samples that were suitable for analysis.

The analysis determined seal thickness, residual asphalt content, density, Marshall stability, flow, and moisture content of seal. The results of these analyses are presented in Table 9.

The average thickness of the admix seal was approximately 15.2 cm (6 in.), which is twice as thick as we originally planned. This increased thickness was due mainly to a lack of depth control of the BOMAG MPH 100 and the lack of desired compaction.

The most critical seal parameter, the residual asphalt content, turned out to be much lower than we had desired. An average of approximately 11.0 wt% residual asphalt was obtained in the admix seal as compared to the 16 to 18 wt% planned. The low asphalt content was a direct result of the increased seal thickness. The 15.2-cm seal was twice that planned (7.6 cm) and the asphalt emulsion was applied at a rate which would have given a 16 to 18 wt% 7.6-cm

TABLE 9. Admix Seal Characteristics

Sample	Admix Seal Thickness, cm	Residual Asphalt, wt%	Density, kg/m^3	Marshall Stability, N	Marshall Flow, mm	Percent Moisture
2 AT	15.2	12.6	1607	2971	0.76	5.5
5 B	16.5	11.0	1717	2914	0.56	3.5
5 BT	15.2	10.2	1669	(a)	(a)	3.6
6 C	16.5	11.2	1684	1890	0.74	1.8
6 CT	15.2	12.9	1679	3172	0.69	2.0
7 D	14.0	11.2	1738	(a)	(a)	3.1
7 DT	15.2	12.3	1772	3812	0.74	4.5
8 A	15.2	9.2	1687	907	0.81	3.1
8 AT	15.2	8.4	1599	(a)	(a)	2.6
Average	15.2	11.0	1684	2611[b]	0.71[b]	3.3

(a) Core Samples did not hold together so Marshall stability and flow tests could not be performed.
(b) Average excludes cores which could not be measured.

seal. With adequate depth control during mixing of the soil stabilizer, the required asphalt content should be obtainable.

Another critical seal parameter was compaction which is correlated through the density of the admix seal. Our results show an average density of 1684 kg/m^3 (105.8 lb/ft^3), which, compared to the expected 1920 kg/m^3 (120 lb/ft^3), is quite low. Several factors contributed to the low density. One factor was that the base tailings were not compacted well. This caused the admix seal to move in front of the compactor during compaction. A lack of water in the tailings was the cause of the poor base compaction. Another factor was the technique used to compact the seal. We used a vibratory roller exclusively in compaction. However, we recently discovered that vibratory rolls are effective only for the first few passes and a static roller must be used to further compact the seals. A third factor was that the seal had not completely cured before compaction was begun. This caused the asphalt emulsions to act as a lubricant between the tailings particles instead of as a cement.

The moisture content of the seal averaged 3.3%, which is slightly high. This indicated that the seal admixture had not "kicked out" enough water prior to compaction and, therefore, was insufficiently cured. This led to some of the problems described previously.

The Marshall stability data, which includes the "flow", is not as absolute a measurement of seal strength as it is in the paving industry because of the high asphalt content. However, it can be used as a relative measurement of strength differences between seals. The data shows that the admix seal was quite weak mechanically compared to asphalt pavement standards. This low strength was due to small aggregate with a narrow size range, high residual asphalt content, and insufficient compaction.

FIELD RADON FLUX MEASUREMENTS

The effectiveness of the asphalt emulsion-tailings seal was determined by measuring radon exhalation from the test area before and after the seal was applied. This involved trapping the radon exhaling from a predetermined area.

Three systems that could be used to accomplish this are: 1) collecting the radon from a nitrogen carrier gas system by passing it through activated carbon in a canister submerged in a dry ice/alcohol bath to maintain a temperature of about -78^{0}C, 2) collecting the radon in a static activated carbon system at ambient temperature, or 3) collecting the radon and its daughters in a scintillation cell of a continuous radon monitor. In this first option, the activated carbon is removed after a specified sample time, sealed in a 15.4-cm-dia plastic Petri dish, allowed 4 h for the daughters to reach equilibrium, and counted. All three options, illustrated in Figure 29, were tested during the field test; however, option 1 was the primary system used. Photos of the radon measurement systems in use during the field test are shown in Figures 30, 31, and 32. The counting system used during the field test is shown in Figure 33.

Laboratory studies indicate activated carbon at low temperatures is the most reliable "trap" for radon gas. Problems with the other systems include: 1) dilution of radon in carrier gas to levels below detection limit of a Lucas Cell, and 2) uncertainty over the ability of activated carbon at ambient temperature to trap and retain all the radon in an enclosed area.

Field measurements were divided between preliminary measurements, and actual site measurements. The preliminary measurements, as outlined below, were undertaken to calibrate the radon collection system.

- Radon measurements were taken over the same exact area using four tents, the objective being to cross-calibrate the tents.
- Radon measurements were taken over a tailings--covered fog seal spread on a steel plate. The objective was to determine the potential error induced by tailings dust blown on the seal.
- Radon measurements were taken over an asphalt emulsion-tailings admix seal under which a steel plate had been placed. The objective was to separate the radon exhalation of the admix seal itself from radon exhalation of the tailings beneath the seal.
- Radon measurements were taken considering the effects of temperature, humidity, and atmospheric pressure.

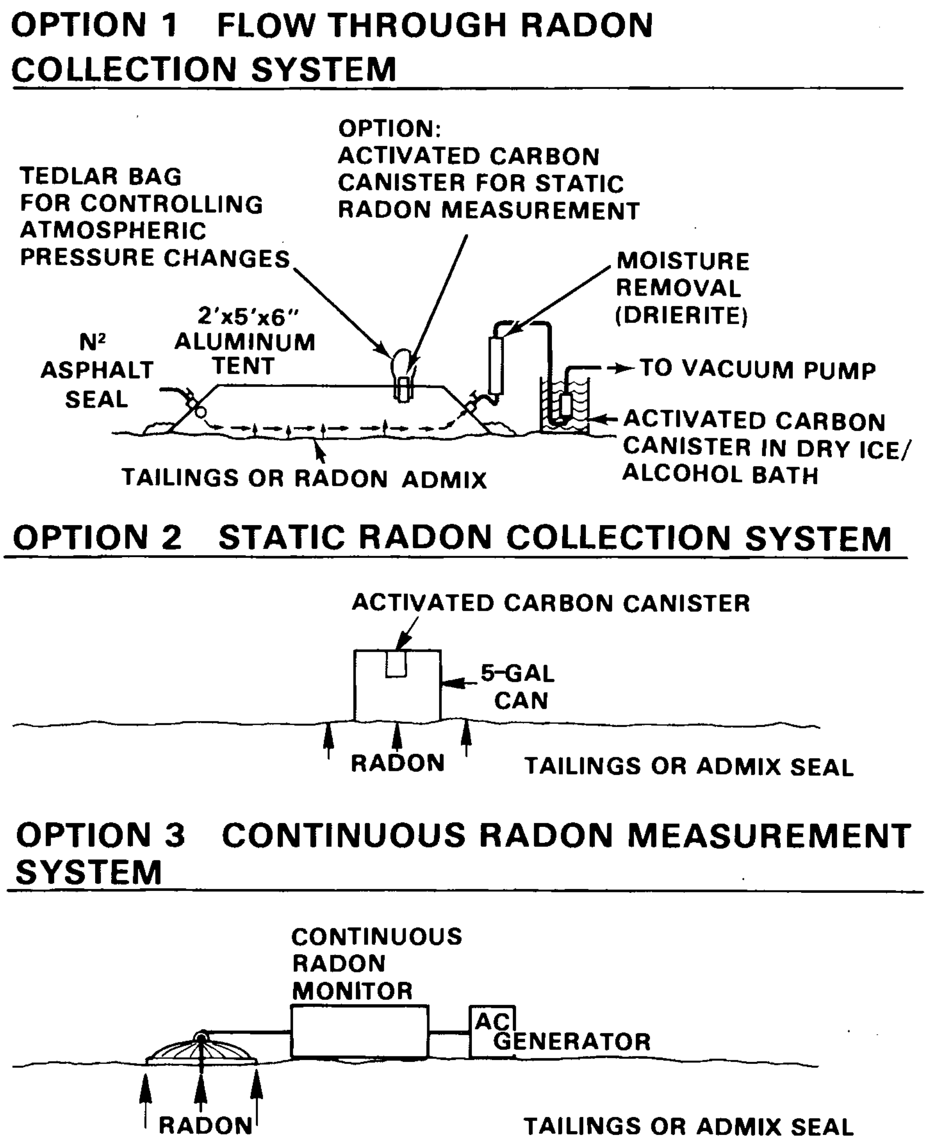

FIGURE 29. Illustration of Radon Measurement System Used for Field Tests

The data obtained enabled us to determine the flux measurements over both bare tailings and sealed areas.

The radon measurements over the bare tailings were performed as control measurements; a base point to compare exhalation before and after sealing was completed. The bare tailings (91.4-m x 91.4-m area) were divided into eight test plots. This was done so that the total sealed test area contained eight separate test areas under different sealing conditions. Four radon flux

FIGURE 30. Radon Measurement System Used for the Field Test

FIGURE 31. Series of Radon Measurement Systems

FIGURE 32. Continuous Radon Monitor

FIGURE 33. Counting System Used During Grand Junction Field Test

measurements were taken on each of these areas. For statistical analysis, three measurements were made on predetermined sites in each separate test area and the fourth measurement was on a randomly selected site (Figure 34).

Radon measurements were taken on the sealed area directly above the previously measured sites. Radon measurements were also made around the sealed

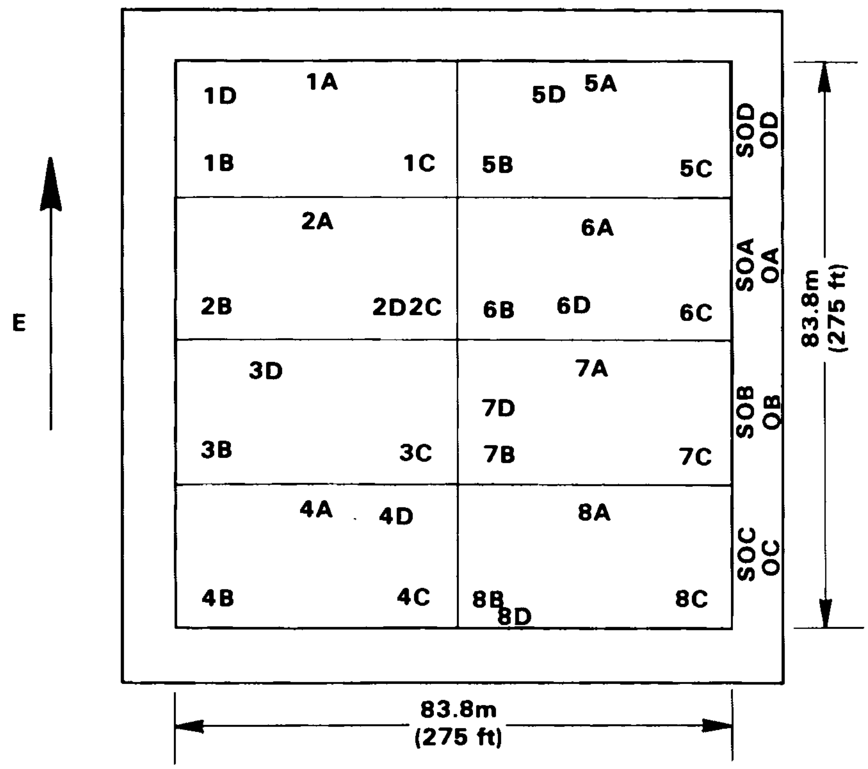

FIGURE 34. Locations for Radon Flux Measurements Before the Seal was Applied

area to determine the change in radon flux around the edge of the sealed test site. The sampling procedure is as follows:

- The tent is placed on the preselected area. For the measurements over the sealed area, the tent edges are sealed to the tailings seal with hot asphalt cement.
- The tent is purged with a high flow rate of nitrogen (425 L/h) for 5 min. Nitrogen flow is then reduced to 283 L/h and allowed to flow through the carbon canister. The vacuum pump is then started and N_2 flow readjusted if needed. The carbon canister must be lowered slowly into the dry ice/alcohol bath at this time.
- Timing for the 4-h test begins when flow is first allowed through the Drierite column and carbon canister. Periodic checks are made on the system flow rate, pressure balance and the dry-ice bath during the test run.

- At the end of the 4-h test period the carbon canister is removed from the bath and nitrogen flow is discontinued. Another carbon canister is connected to the test canister to remove any radon from the air as the canister comes back to ambient temperature. (Since no radon was detected on the second canister this practice was discontinued).
- The Drierite in the dehumidifying columns is changed as needed. The used Drierite is then stored and later counted for any radon.
- The activated carbon is transferred to a 15.4-cm-dia x 2.5-cm plastic Petri dish, sealed, allowed a minimum of 4 h to reach equilibrium, and counted using a counting system (Figure 33) set up in Grand Junction.

Calibration and Precision of Data

The accuracy of our radon flux measurements depends on the radon tent system as well as the gamma detector used for counting the charcoal cannisters. The precision of the radon collection system was determined during the preliminary field measurements. As mentioned earlier these tests account for tent calibration, temperature, atmospheric pressure, humidity and spurious radon sources. The following tests were performed:

1. Two tents were set up immediately adjacent to each other and radon collection was initiated.
2. At the end of the two simultaneous tests, the two other remaining tents were placed on the same identical spots, and radon collection was again initiated.
3. Once the second pair of tests was concluded, the tents were switched so that each occupied the spot previously held by the other. A final radon collection was then taken.

From the test data, the radon fluxes were then determined. The standard deviation of the data on one of the adjacent measurement sites was 32% while on the other was 23%. These values indicate that flux measurement reproducibility is within $\sim$32%, independent of: 1) humidity, temperature, and pressure fluctuations; 2) tent differences, and 3) the time of day when measurement occurs.

Two tests were conducted to determine any experimental bias due to contaminated measurement surfaces. The objective of the first test was to determine the effect of radon exhalation from the admix seal itself. The data were obtained by measuring the radon over an asphalt emulsion/tailings admix seal which was separated from the tailings base by a steel plate. The second test determined the effect of tailing's dust contaminating the surface of the fog seal. A contaminated fog seal was modeled by pouring asphalt emulsion onto a sheet of metal and then sprinkling fine dried tailings (slimes) over the surface. The radon flux over this surface was then measured. Since the measured radon flux in both tests was within the counting error of the gamma detector, we concluded that the two possible biases were negligible.

The calibration and precision of the gamma-ray detector used in the Grand Junction field test also influenced the reliability of our flux measurements. The intrinsic germanium diode used for gamma ray detection was calibrated by recounting five of the samples initially counted at the Grand Junction facility on PNL's multidimensional NaI system. Comparison of the counting data delivered an average efficiency that was then used to calculate fluxes. The low efficiency obtained for the intrinsic germanium detector (0.397%) is due to: 1) the inherent geometrical effects of a one-dimensional system, 2) the relatively large-sized carbon samples, and 3) low efficiency of the germanium detectors.

Results of Field Radon Flux Measurements

In order to determine the effectiveness of the asphalt emulsion seal, radon flux measurements were made before and after seal application using the radon measurement technique previously described. Radon flux results are summarized in Tables 10 and 11.

Before-Seal Fluxes

The purpose of measuring the flux on the bare tailings was for comparison with the after-seal fluxes in order to determine the effectiveness of the seal. The radon fluxes from the Grand Junction tailings pile ranged from 12 to 2400 pCi/($m^2 \cdot s$). The average flux was 270 pCi/($m^2 \cdot s$) while the geometric mean was 73 pCi/($m^2 \cdot s$). Radon fluxes prior to seal application are shown in Figure 35 and Table 10.

TABLE 10. Radon Fluxes from Grand Junction Tailings Site

Test Plot[a]	Radon Flux, pCi/(m^2•s) Before-Seal Flux	After-Seal Flux	% Reduction (increase)
1A	2380	85.5	96.4
1B	333	2.17	99.3
1C	1650	(b)	--
1D	1610	(b)	--
2A	234	194	--
2B	106	(b)	--
2C	54.0	(b)	--
2D	153	(b)	--
3B	124	(b)	--
3C	110	(b)	--
3D	103	(b)	--
4A	36.7	(b)	--
4B	25.4	(b)	--
4C	57.1	(b)	--
4D	62.5	(b)	--
5A	68.0	218	(221)
5B	228	60.3	73.5
5C	28.5	55.5	(94.7)
5D	217	2.7	98.8
6A	36.0	1.22	96.6
6B	30.6	74.8	(144)
6C	112	11.1	90.1
7A	89.2	19.8	77.8
7B	89.2	36.7	58.9
7C	89.2	27.4	69.3
7D	89.2	7.13	92.0
8A	73.2	69.9	4.5
8B	51.5	2.89	94.4
8C	94.8	5.61	94.1
8D	27.9	0.892	96.8
0A	(c)	41	--
0B	(c)	39	--
0C	(c)	71	--
0D	(c)	180	--
S0A	(c)	22	--
S0B	(c)	12	--
S0C	(c)	96	--
S0D	(c)	73	--
2ES	1250[d]	0.68	99.2
1NFA	1250[d]	651	49.9
2NEF	1250[d]	109	91.6
FSE	1250[d]	369	70.5
FSW	1250[d]	3.46	99.7
NA	89.2[e]	58.5	34.4
NB	89.2[e]	198	(122)
NC	89.2[e]	18.5	79.3
ND	89.2[e]	36.1	59.5

(a) The locations of the test plots are shown in Figure 36.
(b) No seal was actually applied in these areas.
(c) No before-seal measurement was taken.
(d) Average flux for upper slimes region.
(e) Average flux for sandy regions.

TABLE 11. Radon Fluxes from Grand Junction Tailings Site Measurements on Overburden

Test Plot[a]	Radon Flux, pCi/(m^2·s) Before-Seal Flux[b]	After-Seal Flux	% Reduction (increase)
H01	89	51	42.7
H02	89	130	(46.1)
H03	89	130	(46.1)
H04	89	57	36.0
H05	89	50	43.8
H06	89	57	36.0
H07	89	17	78.3
H08	89	24	70.1
A[c]	89	0.45	99.5
B[c]	89	0.40	99.5
C[c]	89	0.25	99.7
D[c]	89	0.21	99.8

(a) Locations of the test plots are shown in Figure 39.
(b) Average flux for sandy region.
(c) Static carbon canister set up was used for these measurements.

The large range of radon fluxes was due to the fact that the tailings pile consisted of segregated sands and slimes material (see Figure 35). The slimes were higher in radium content and therefore had higher radon fluxes. There was no flux measurement taken in area 3A due to a malfunctioning vacuum pump for one tent. Also, fluxes for area 7 are not available because the carbon canisters from the tests were lost due to improper sample identification.

In areas where actual radon measurements were not made but a bare tailings flux was needed for comparison to after-seal flux, an average flux was assumed. For test areas 7, NA, NB, NC, ND, and H01 thru H08, an average of all the radon fluxes for sandy regions was used. For areas 2ES, INFA, 2 NEF, FSE, and FSW an average of the fluxes in the northeast slimes region was used. The reason the average for the slimes did not include the slimes in the northwest corner is

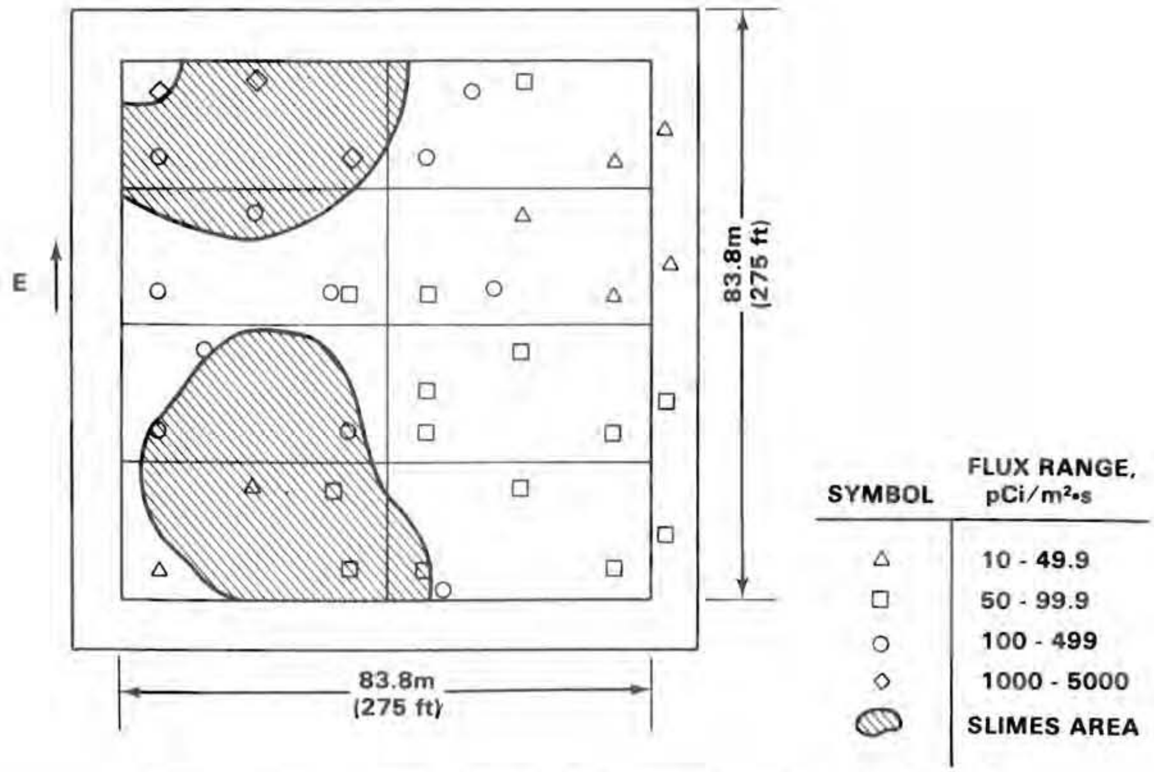

FIGURE 35. Radon Fluxes from Grand Junction Tailings Site Prior to Seal Application

that these slimes were of a different nature (mixed with sand) than those in the northeast corner. In addition, the northeast corner slimes were the ones that were actually sealed.

After-Seal Fluxes and Effectiveness of the Seal

Radon flux measurements were made after the application of the asphalt emulsion seal to evaluate the effectiveness of the seal. The locations of these tests are shown in Figure 36. A summary of the results is presented in Table 10 and Figure 37. The radon fluxes ranged from 0.89 to 651 pCi/(m^2•s). The average and mean were 47 and 20 pCi/(m^2•s), respectively. Based on the before-seal and after-seal flux measurements for each test spot, reductions of radon fluxes were calculated. They ranged from 4.5% to 99.4% in areas where before- and after-seal radon flux measurements were made and 26.9% to 99.9% in areas where the before-seal flux was estimated. In some areas an increase in

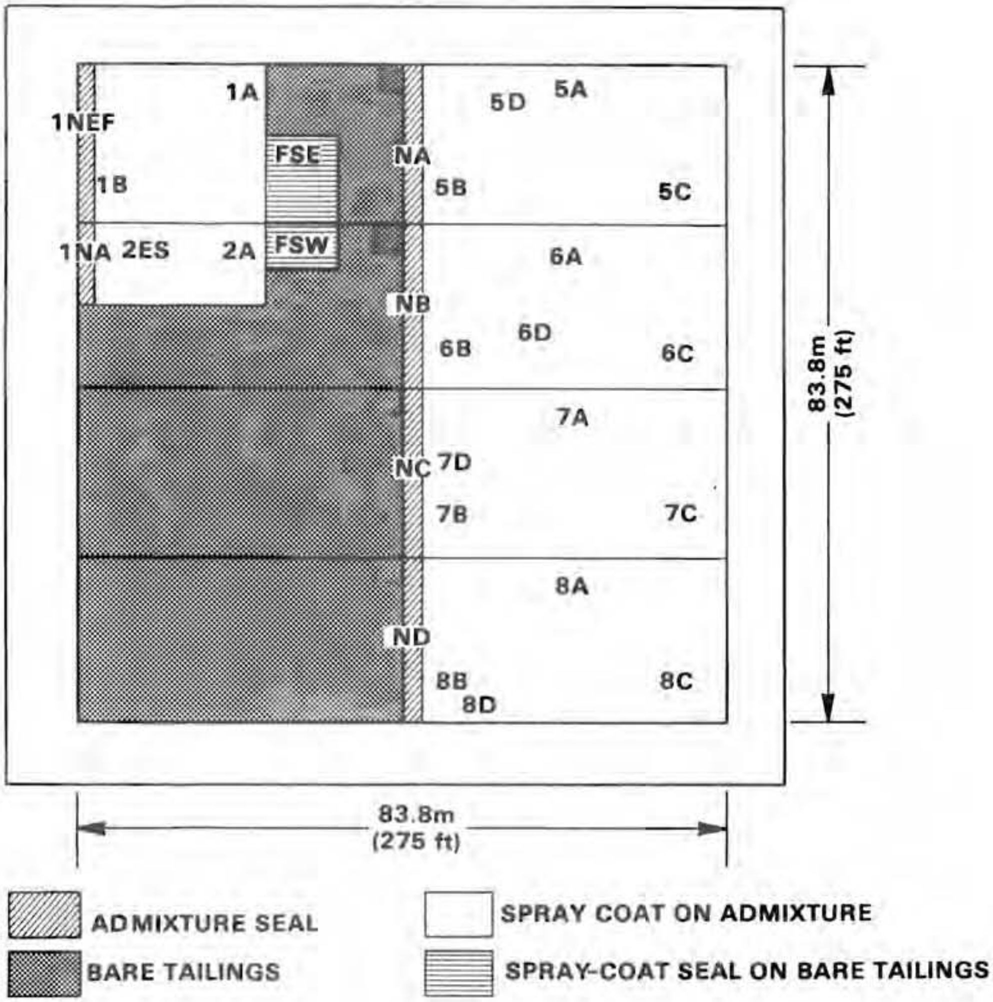

FIGURE 36. Location of Test Plots for After-Seal Radon Flux Measurements

flux was observed. These increases ranged from 57.5% to 221%. Overall, 85.7% of the areas showed a reduction in radon exhalation with an average flux reduction of 75.5%.

It can be seen in Figure 38 that the seal had a definite effect on the radon exhalation. Before the seal was applied, approximately 50% of the radon fluxes measured were in the 0 to 99 pCi/($m^2 \cdot s$) range. After the seal was applied, nearly 80% of the fluxes fell in this range. Also, before the seal was applied, fluxes as high as 2400 pCi/($m^2 \cdot s$) were encountered. After the

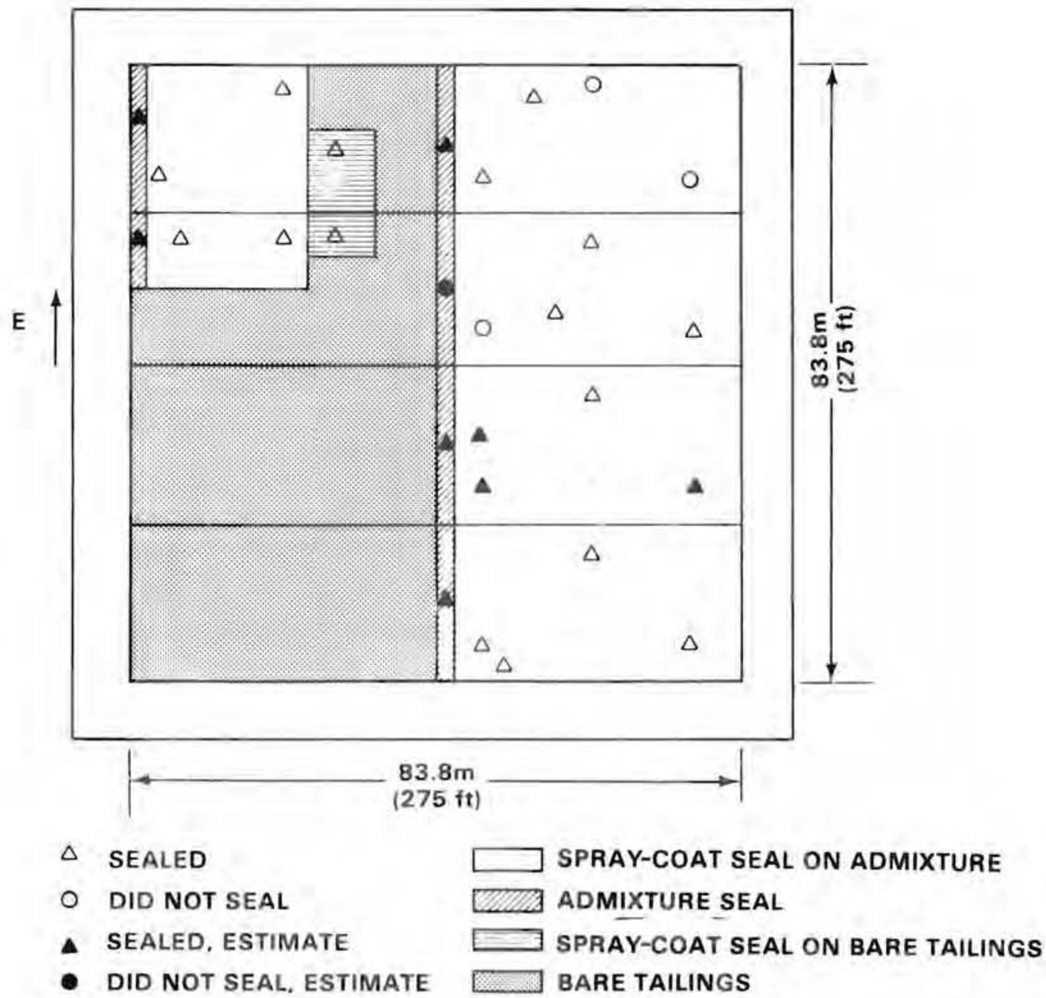

FIGURE 37. Test Plots on Seal Which Did and Did Not Reduce the Radon Flux

seal was applied, the highest flux measured was 651 pCi/(m^2•s). Although the seal was not totally effective, it did have a significant effect on the radon exhalation of the tailings pile.

The seals applied to the Grand Junction tailings pile were of three types. The admixture seal, admixture seal plus a spray-coat seal, and a spray-coat seal on bare tailings. Areas that were sealed are shown in Figure 37.

The admixture seal was a moderate success. Only one test spot reduced the radon exhalation by greater than 90%. This was in an area that had a high asphalt content. However, five out of the six test areas measured on admixture

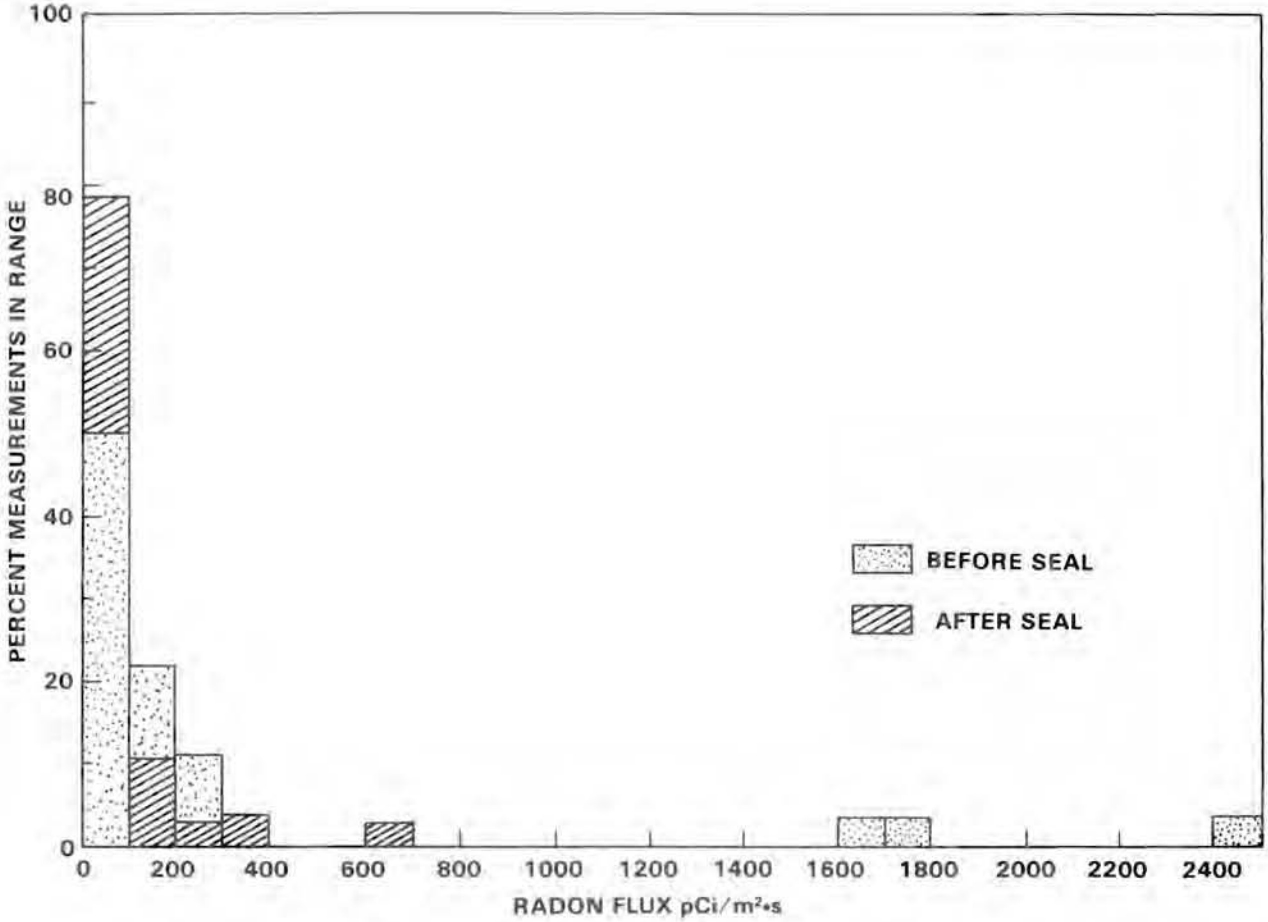

FIGURE 38. Distribution of Radon Fluxes Before and After the Seal was Applied

seals showed some reduction in radon flux. It is surprising that the admixture sealed at all, considering that the average residual asphalt was actually only 12.4 wt%. These preliminary results suggest that a higher residual asphalt content (18 to 20 wt%) in the admix seal could reduce radon exhalation by greater than 90%. The admixture area that did not seal possibly had transverse cracks created during compaction.

The admix seal covered with a spray coat was quite successful. Seventeen out of 20 test spots showed reduction in radon flux. In addition, 10 of the 17 areas showed greater than 90% reduction in flux. On the high residual asphalt test plot, all of the test spots reduced radon exhalation. At three of these four test spots the seal reduced radon exhalation by greater than 96%.

Three tests spots showed an increase in radon exhalation. Transverse cracking of the admix seal and poor bonding of the spray-coal seal are attributed to the increase in flux. In addition, deep tire ruts were present in some of these areas which would cause leaks in the admix spray-coat seal.

Only two measurements were made on the spray-coat seal that was sprayed directly on bare tailings. The results of this limited sampling was quite good with a 99.7% and 70.5% reduction in flux. However, the mechanical stability of this seal was very poor and would be of no use in this particular application. This type of seal would be useful in applications where very few mechanical forces are anticipated.

Radon Fluxes After Overburden Application

In order to determine the effects on the admix spray-coat seal of driving equipment on the overburden, radon flux measurements were made on top of the overburden. The test areas used are shown in Figure 39.

Tests H01 thru H08 were made using the nitrogen flow through radon measurement system. Tests A through G were made using the tents with a static carbon canister. Due to lack of time Tests E through G were not made.

The results of the measurements are presented in Table 11. It is apparent from this data that the seal was partially destroyed in test areas H01-H08 during the applications of the overburden. This destruction probably can be attributed to the fact that the initial overburden application was about 7.6 to 15.2 cm (3 to 6 in.) deep. The seal was damaged when the tractor and the herbicide truck drove over this thin covering. The major reason for the damage to the radon seal is that the spray-coat seal was stopping most of the radon. When this fragile part of the seal was abused, radon escaped. If the admixture seal were properly installed, its greater mechanical strength would resist the kind of damage that occurred to the spray-coat seal.

From the first set of measurements from test areas A thru D, it appears that the application of the overburden did not damage the seal. In fact, the average radon flux reduction was much greater after the overburden application than before. This is possibly because measurements made on the overburden were not made on the same spots as before the overburden was applied. Also, due to

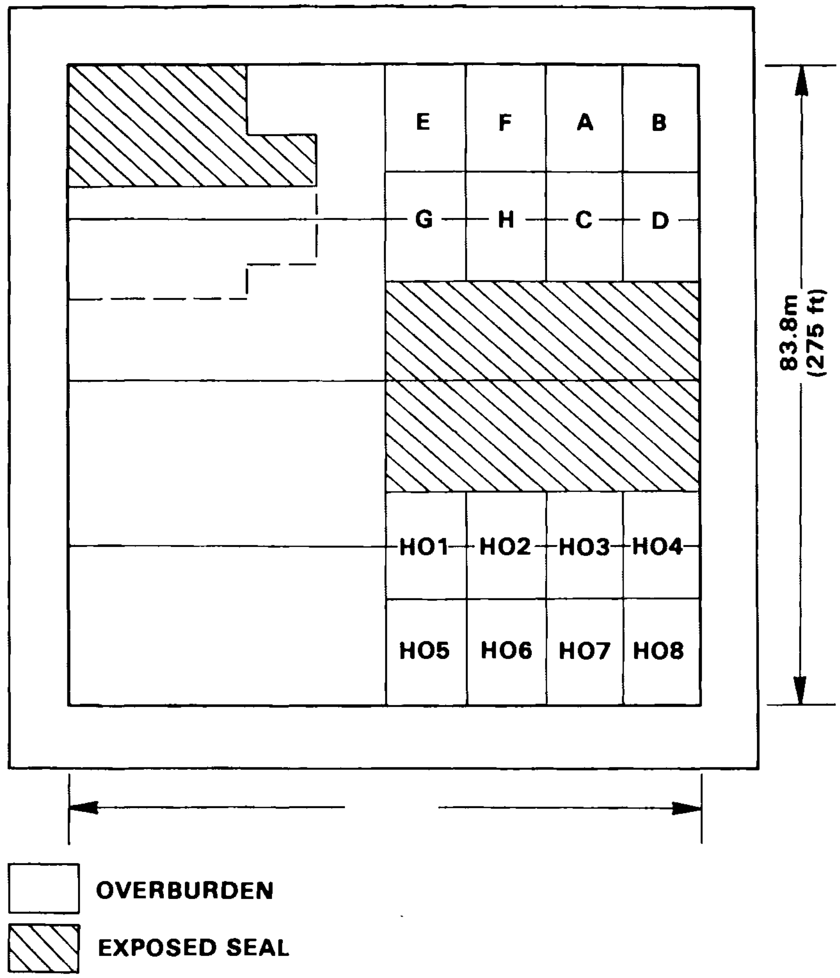

FIGURE 39. Location of Test Plots for Radon Measurements on Top of Overburden

the long sampling period (19 days), the effectiveness of the static carbon canisters measurements is very poor. However, even assuming the fluxes were an order of magnitude higher than measured, a reduction in radon flux is still realized. Partial credit for the reduced radon flux is due to the 20 to 30 cm (8 to 12 in.) of overburden that had a high clay content.

PROBLEM AREAS

After reviewing the results of the initial field tests, several problems related to application equipment and seal formulation were identified.

Application Equipment Problems

The identified problems included depth control, mixing, and compaction. The problem of depth control was primarily due to insufficient compaction of tailings during site preparation which resulted in lack of stabilizer tire traction. Therefore it was difficult to control admix depth and the residual asphalt content which varied from about 18 to 13 wt%. An 18 to 20 wt% residual asphalt is required in order to obtain a suitable seal. This problem can probably be overcome by some equipment modifications and improved tailings compaction.

Mixing of the asphalt emulsion with the tailings was not satisfactory. The primary reason was the lack of water in the tailings prior to emulsion addition. Also the blade design of the BOMAG MPH 100 stabilizer is not totally suitable for good mixing since its primary purpose is to tear up old asphalt pavement and remix with low concentrations of asphalt emulsion, e.g., 3 to 6 wt% asphalt. This problem probably can be overcome by some equipment modifications.

Compaction of the admix seal was not totally satisfactory partly because the underlying tailings were not properly compacted. Also, vibratory compaction of the admix is not completely suitable because of the high pressure on this material. A rubber-tired roller would probably be more satisfactory because of its ability to knead the admix material as it compacts.

Seal Stability Problems

The primary problem of seal stability resulted from the previously discussed equipment problems. However, some additional problems did occur. The lack of water in the tailings prior to emulsion addition caused the emulsion to break in some areas prematurely. This lack of water also contributed to poor coverage of the tailings particles with emulsion (Figure 40).

Another problem was an increase in the rate of water vapor transmission through the admix seal because the seal was not a total gas/water vapor seal. Accompanying this water vapor were many salts, which precipitated throughout the admix seal as well as on top of the seal (Figures 41 and 42). This salting problem was caused by 1) a non water-vapor seal and 2) the admix being a black

FIGURE 40. Core Sample Taken from the Admix Seal Showing Poor Particle Coating

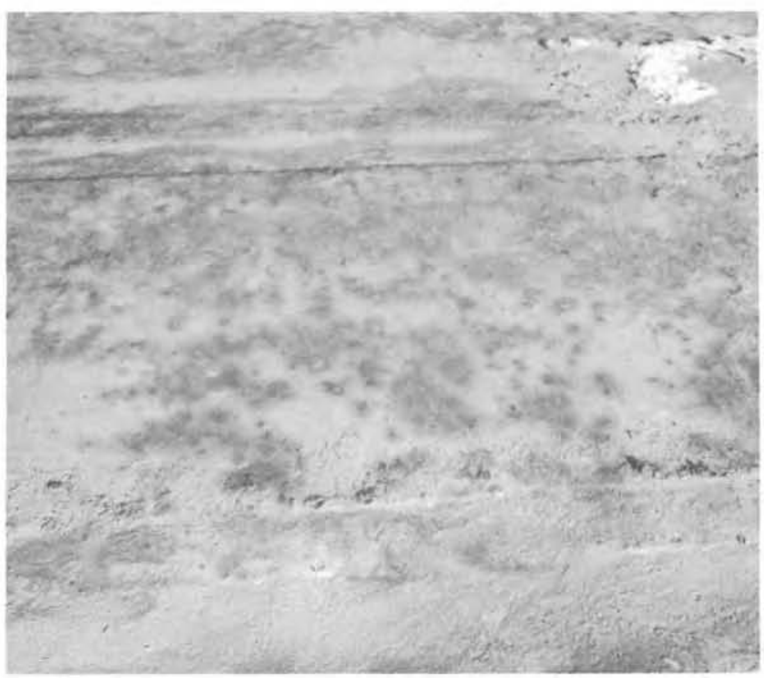

FIGURE 41. Salts Transporting Through Admix Seal at Slimes Area - December 1979 Grand Junction

FIGURE 42. Salts Transporting to the Surface of Grand Junction Tailings on Bank Near Colorado River - December 1979

surface caused an increase in transport of water carrying salts to the surface. This salting problem occurred only in those areas that were not covered with overburden and in the areas where mostly slimes with a high salt content were present. The salting problem would not have occurred if there had been a total admix seal where water vapor could not transport to the surface. The salting problem is being examined more closely to determine the exact composition of the salts and the methods of transport.

Another problem occurred several months after the field test when an area about 6 m (19.5 ft) subsided (Figure 43). It is speculated that one or more of three possible mechanisms caused this subsidence. There could have been enough water movement through the tailings to physically remove some of the underlying tailings. A second possible mechanism is a phenomena called "piping". Piping is the dispersion of the clay in the soil due to a high

FIGURE 43. Sink Hole at North Edge of Area 7

sodium content in relation to the calcium, potassium, and magnesium in the soil. This dispersion of the clays leaves void spaces, which might have caused the tailings to collapse upon themselves. The third mechanism is that of a structural defect in the tailings which gave way after the seal had been laid down. These mechanisms are purely speculations, and further studies are being conducted to determine the true cause of the subsidence.

ESTIMATED COST OF ASPHALT EMULSION TAILINGS SEAL

Laboratory studies and a preliminary field test have indicated the potential effectiveness of the asphalt emulsion tailings seal, but no cost optimization has yet been considered. In comparison to most alternatives, this stabilization sealing method shows promise in being cost effective. For example, comparing 1) the application of a 7.6-cm (3-in.) admix seal containing 20 wt% residual asphalt and having a 0.61-m (2-ft) overburden with 2) the application of 3.0 m (9.8 ft) of soil cover to achieve greater than 90% radon flux reduction, we calculate the estimated costs presented in Table 12.

As seen from the cost comparison, the asphalt emulsion sealing procedure is potentially cost effective. However, much additional work needs to be done before optimized procedures can be worked out. There is no one solution to the problem of radon exhalation from uranium tailings. Tailings stabilization procedures should be site specific. In some areas, other alternatives such as

TABLE 12. Estimated Cost to Stabilize and Seal 1 Acre of Uranium Mill Tailings

	Estimated Cost per Acre[a]	
	Overburden System	Asphalt Emulsion System
Materials Cost		
Overburden	\$57,200.00	\$11,600.00
Asphalt Emulsion	--	\$25,000.00
Site Preparation, Application, Revegetation, etc.	\$ 2,500.00	\$ 4,500.00
TOTAL	\$59,700.00	\$41,100.00
TOTAL COST/m^2	\$24.80	\$10.10
TOTAL COST/yd^2	\$12.40	\$ 8.50

(a) These costs are based on overburden at \$3/yd^3 and asphalt emulsion at 55¢/gal.

use of clay caps or the 3-m (9.8-ft) soil coverings may still prove to be more cost effective. A concerted effort is needed to review and consider all the available alternatives before a final decision is made as to what procedure is to be used for each site.

CONCLUSIONS

General conclusions based on the laboratory and field tests are as follows:

- Cationic asphalt emulsion can be used effectively to stop radon exhalation from uranium tailings by either pouring/spraying the emulsion over the tailings or admixing the emulsion with the tailings. Proper selection of the emulsion depends on the physical-chemical properties of the tailings or soil to be sealed.
- Both laboratory and field tests indicate the potential for a flux reduction of greater than 99%. Field test radon flux reduction at the Grand Junction tailing test site averaged 76%.
- An admix seal using Grand Junction tailings as the mix aggregate must contain about 18 wt% residual asphalt in order to achieve a total seal.
- Long-term stability of the seal is affected by the nature of the environment surrounding the seal. For example, if the seal were exposed to sunlight, ultraviolet degradation would occur and the seal would not last 1000 yr.
- Maintaining overburden over the seal provides erosion control. Revegetation or a rip-rap (rock) cover could be used to prevent soil erosion.
- In order to meet the proposed EPA standard of 2 $pCi/(m^2 \cdot s)$ (average annual flux) at the Grand Junction test site an average radon reduction of greater than 99% is required.
- The asphalt emulsion sealing system is cost competitive with alternative techniques. In general, it would be less expensive than the addition of 3 m of overburden--the current NRC minimum requirement.

RECOMMENDATIONS

The FY-1979 program was quite successful in that it demonstrated that uranium tailings can be radon sealed in the field. A great deal of knowledge was obtained from both the laboratory studies and the Grand Junction field test. This knowledge helped us to make the following recommendations to improve the FY-1980 program.

Laboratory Studies

- Determine optimum asphalt emulsion seals for a variety of tailings using several types of asphalt emulsion. Also, use aggregate sources other than the tailings themselves to make seals.
- Perform a complete characterization of these tailings including size distribution, chemical makeup, void space, and clay content.
- Determine the aging characteristics of the asphalt emulsion seals including resistance to oxidation, corrosive chemical environment, ultraviolet light, mechanical abuse, etc.
- Determine the biodegradation of the asphalt emulsion admix seal including microbial degradation. Laboratory studies should address these concerns as well as tailings sampling.
- Determine the effects of temperature and gas flow rate on activated charcoal and its ability to capture radon.
- Improve radon measurement system for laboratory radon diffusion measurements.

Field Studies

In addition to the use of the BOMAG MPH 100, alternative seal application techniques, such as the use of a pug mill-paver, slurry seal machine, or a combination of previously mentioned equipment, should be investigated. These alternative methods should a) have the ability to handle high residual asphalt contents, b) demonstrate good mixing with fine aggregate, c) use currently available equipment, and d) have the ability to move on a poorly compacted base. It is recommended that further field studies investigate methods for applying a stable base more suitable for equipment motivation before seal application. Also other methods of base and seal compaction should be examined, and an improved radon measurement system should be developed for use in the field.

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ACKNOWLEDGMENTS

We wish to thank the following people and companies who participated in the field test and helped make it a success. Alan Roberts, Roberts Construction Co., who supplied the BOMAG MPH 100; H. W. Moore Equipment Co. who supplied the BOMAG Vibratory Compactor; Dave Wolter, Kochring Co., for his help and advice; Jack Dybalski, Armak Company, for helping to develop apshalt emulsion formulation; Don Arnold, Don Arnold Construction Company, for supplying heavy construction equipment; Utah Emulsion for supplying the apshalt emulsion; Dick Walton, Walton Trucking Co., for supplying the distributor truck; and Lincoln Devore Testing Laboratory, for laboratory services.

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D. Dressen
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Oak Ridge, TN 37830

Al Askew
Politech Corporation
2220 Austin National Bank Tower
Austin, TX 78701

M. L. Matthews, Project Engineer
Uranium Mill Tailings Project Office
U.S. Department of Energy
P.O. Box 5400
Albuquerque, NM 87115

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