DOE/UMT-0201
PNL-3752
UC-70

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May 1981

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-3752

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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# ABSTRACT

Studies of asphalt emulsion sealants conducted by the Pacific Northwest Laboratory have demonstrated that the sealants are effective in containing radon and other potentially hazardous material within uranium tailings. The laboratory and field studies have further demonstrated that radon exhalation from uranium tailings piles can be reduced by greater than 99% to near background levels. Field tests at the tailings pile in Grand Junction, Colorado, confirmed that an 8-cm admix seal containing 22 wt% asphalt could be effectively applied with a cold-mix paver. Other techniques were successfully tested, including a soil stabilizer and a hot, rubberized asphalt seal that was applied with a distributor truck. After the seals were applied and compacted, overburden was applied over the seal to protect the seal from ultraviolet degradation.

## SUMMARY

In a study sponsored by the U.S. Department of Energy's Uranium Mill Tailings Remedial Action Project (UMTRAP) Office, the Pacific Northwest Laboratory (PNL) is investigating a promising concept in which uranium mill tailings are covered with an asphalt-emulsion sand admixture seal.

The study has demonstrated that the seals are effective on a short-term basis in containing radon and other potentially hazardous materials within uranium tailings. With the seals, radon exhalation from uranium tailings piles can be reduced by greater than 99.9% to less than the U.S. Environmental Protection Agency (EPA) standard of 2 $pCi/m^2 \cdot s$ above background. The study further indicated that the seals potentially have the physical and chemical properties required for long-term effectiveness.

This report details laboratory and field studies conducted by PNL as a continuation of the 1979 research. The laboratory studies included tailings and seal aggregate characterization, seal formulation, radon diffusion measurements, and assessment of seal stability. The field studies included evaluation of application technology, development of an improved radon flux field measurement system, and field tests at the tailings pile in Grand Junction, Colorado.

The results of the fiscal year 1980 study are summarized below.

### LABORATORY STUDIES

- Radon flux reductions of greater than 99% were achieved by using an admix seal ≈7.6 cm thick. The seal was composed of cationic asphalt emulsion and aggregate material such as tailings, blowsand, or concrete sand. The resulting seal contained 22 to 25 wt% residual asphalt on a dry aggregate basis.[a]
- The physical-chemical properties of the tailings have a significant effect on seal formulation. Most tailings have a high silt content

(a) Wt asphalt/wt aggregate (all residual asphalt contents in this report are on a dry aggregate basis).

(high surface area), which makes them a poor aggregate material for admix seals. An aggregate such as local blowsand or concrete sand must be used in place of the tailings if a suitable seal is to be achieved. For this study, concrete sand was selected as the standard seal aggregate because it had the most reproducible particle size distribution and should be available near most tailings sites. The chemical composition of the tailings and the water-soluble salts was determined at the Grand Junction field test site. Major components of the tailings were K, Ca, Fe, and Si. The water-soluble salts consisted primarily of Ca, Na, Mg, K, Si, $SO_4$, Cl, and $NO_3$.

- Effects were determined of asphalt emulsion type and concentration, asphalt source, temperature, mixing variables, and herbicide addition on seal quality and characteristics. As a result, two asphalt emulsions were selected for field testing:
  - Armak 4868 +18 mV - soil stabilizer, portable pugmill
  - Armak +78 mV - cold-mix paver, portable pug mill, transit mixer.
- A literature search was conducted in conjunction with laboratory analyses to review seal stability and lifetime of the radon seal. The anticipated mechanisms that could have potential effects on the longevity of the seal are
  - autoxidation
  - microbial attack
  - aqueous leaching
  - temperature cycling (freeze-thaw) stresses
  - tailings subsidence.
- Based on the laboratory studies, a radon barrier system consisting of a 7.6-cm thick asphalt-emulsion admix seal covered with at least 1 m of overburden was recommended for the 1980 Grand Junction field test. The admix seal was to contain 22 to 25 wt% residual asphalt.

## FIELD STUDIES

- Promising application techniques identified for seal application were
  - cold-mix paver
  - portable pug mill and standard paver
  - batch plant and standard paver
  - transit mixer and standard paver
  - slurry sealer
  - soil stabilizer.

  These were identified by carrying out a literature search, contacting asphalt paving industry representatives, and conducting small-scale equipment screening tests.

- Four primary admix-seal application techniques were tested at the Grand Junction site: 1) soil stabilizer, 2) cold-mix paver, 3) continuous pug mill and paver, and 4) transit mixer and paver. In addition three application techniques using a distributor truck to spray-on the seal were tested: 1) a multilayer sand seal, 2) a fog seal, and 3) a hot rubberized asphalt seal.

- A soil stabilizer was used to apply and mix ~5 wt% residual asphalt directly to the tailings. This mixture was then compacted to form a stable base for equipment operation. The base was effective in supporting all equipment except the 41-t cold-mix paver. For this paver, a 5-cm thick -3/4-in. road base was spread over the stabilized tailings and compacted.

- The cold-mix paver showed the most promise for applying the admix, based on ease of application and the resulting seal. The soil stabilizer was able to apply a seal in situ, but mixing problems were encountered because of the varying tailings particle size distribution. Preliminary tests with the concrete truck and the pugmill were unsuccessful; therefore, these techniques were not further tested. The sprayed-on techniques were successful in reducing radon flux, but they lacked the mechanical properties needed for long-term effectiveness.

- An improved radon flux measurement system was designed, fabricated, and used for the 1980 Grand Junction field tests. This system used activated carbon at ambient temperatures to eliminate problems associated with the 1979 radon collection system. Also, the system was designed to eliminate the effects of meteorological changes on the measurement system.

- Radon fluxes prior to seal application ranged from 86 to 1150 $pCi/m^2 \cdot s$ with an average flux of 409 $pCi/m^2 \cdot s$ measured with the PNL radon flux measurement system.

- Radon fluxes after all seal applications ranged from 0 to 344 $pCi/m^2 \cdot s$ with an average flux of 10.0 $pCi/m^2 \cdot s$.

- The test area paved with the cold-mix paver had the lowest radon flux exhalation; fluxes ranged from 0 to 0.6 $pCi/m^2 \cdot s$ with an average flux of 0.2 $pCi/m^2 \cdot s$. This corresponds to an average flux reduction greater than 99.9%, which is significantly less than the EPA standard (2 $pCi/m^2 \cdot s$ above background).

- The seal was capped with 0.3 to 1.2 m (1 to 4 ft) of soil overburden and was revegetated to protect the seal from potential degradation. A biological barrier was placed over a portion of the seal to determine root penetration and animal intrusion. The barrier consisted of a herbicide, Treflan®, and rock cover. Results of this will be reported in another UMTRAP-sponsored PNL project.

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## INTRODUCTION

Uranium mill tailings contain radionuclides that can be potentially hazardous to the environment. Methods to stabilize or dispose of the tailings in a safe and environmentally sound manner are needed to minimize radon exhalation and other environmental hazards.

Under contract to the U.S. Department of Energy's Uranium Mill Tailings Remedial Action Program (UMTRAP) office, the Pacific Northwest Laboratory (PNL) is investigating a promising concept to contain radon exhalation and other potentially hazardous materials in the tailings with an asphalt emulsion seal. Figure 1 illustrates the radon barrier concept of sealing a tailings pile with an admix seal containing asphalt emulsion and a selected aggregate. In 1979, laboratory and field tests were commenced to examine asphalt emulsion sealing procedures and to evaluate seal effectiveness. Based on the results of the 1979 study, further laboratory and field tests were conducted in 1980.

The 1979 laboratory studies determined that a radon flux reduction of greater than 99% could be achieved by using either a 3- to 7-mm poured-on

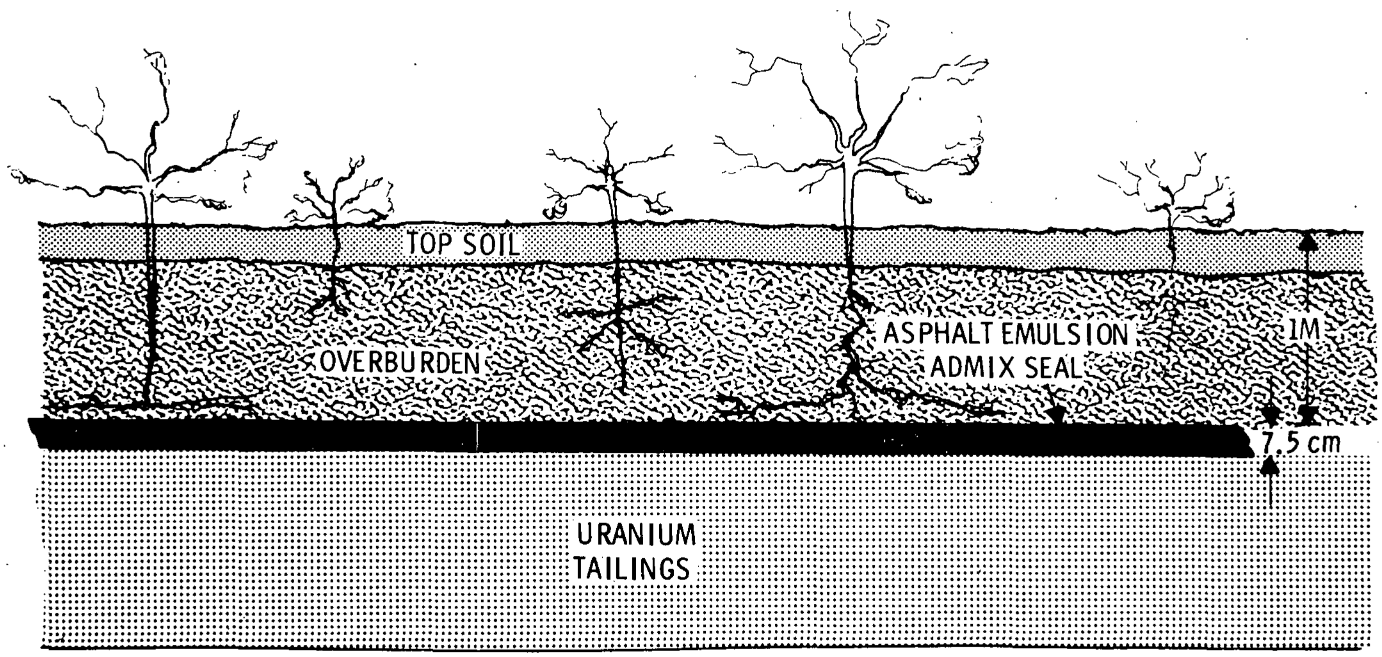


FIGURE 1. Asphalt Emulsion Radon Barrier System

cationic asphalt emulsion seal or a 7.6-cm compacted admix seal of tailings and emulsion containing 18 to 20 wt% residual asphalt. The study further determined that because the physical and chemical properties of the tailings significantly affect seal quality, an admix seal needs an alternative aggregate source such as blowsand or concrete sand.

The 1979 field tests demonstrated that if a soil stabilizer is used to apply the seal in situ, proper equipment operation and amount of water added to the tailings prior to emulsion addition are important in achieving an effective seal.

Overall results of the 1979 study determined that further laboratory characterization and analyses of various tailings and seal aggregates would be beneficial. Additionally, alternative seal applicaion techniques should be investigated, and an improved radon measurement system should be developed for use in the field.

In 1980, laboratory and field studies were continued to evaluate the effectiveness of various asphalt emulsion sealing systems. Laboratory studies included uranium tailings and seal aggregate characterization, seal formulation, radon diffusion measurements, and assessment of long-term seal stability. The field studies included review and evaluation of application technology, development of an improved radon-flux measurement system, and actual applications of sealants. The effectiveness of the seal was determined by measuring radon exhalation before and after seal application. The long-term stability testing of the seal was conducted to determine the effects of chemical (oxidation, aqueous leaching) and physical (mechanical, freeze/thaw, animal intrusion and root penetration) degradation.

The asphalt-emulsion admix radon seal is a radon-gas barrier with desirable properties for long-term stability. The barrier system consists of an ~8-cm-thick asphalt-emulsion/aggregate admix that is covered by ~1 m of overburden. The asphalt-emulsion/aggregate admix layer acts as a radon-impermeable diffusion barrier, and the overburden protects and stabilizes the admix. The admix is a mixture of cationic asphalt emulsion and fine concrete sand. After curing, the admix is ~25 wt% asphalt on a dry aggregate basis and ~1 wt%

residual water. Although the admix has greater structural strength than pure asphalt, the admix will cold flow over a period of time and is fairly ductile. The concrete sand is a much finer aggregate than that used in normal asphalt road pavements. Therefore, the admix has a higher asphalt-aggregate bonding surface area per unit volume than normal road pavements. The very high asphalt content, coupled with the fine aggregate, gives the admix seal a very low void volume when compared to road pavement. The overburden protects the admix seal from sun exposure, rain, extreme temperatures, and sudden temperature changes. The overburden reduces $O_2$ exposure and protects the asphalt from auto-oxidation initiators in the atmosphere and intrusion by the local fauna. The asphalt-emulsion admix seal and the protective overburden form an integral radon-barrier system that is designed for long-term stability.

This paper presents results of the summer 1980 field test conducted at Grand Junction, Colorado, and discusses the progress of this ongoing project, including laboratory and field studies.

## CONCLUSIONS

Several general conclusions can be made as a result of the laboratory and field tests.

- Asphalt-emulsion-aggregate admix with proper application techniques or poured-on asphalt emulsion seals are effective in reducing radon exhalation from uranium tailings to less than the proposed EPA standard (2 $pCi/m^2 \cdot s$ above background).
- Radon-flux reductions greater than 99% were achieved during the 1980 Grand Junction field test (i.e., less than 1 $pCi/m^2 \cdot s$) when measured with the PNL-developed radon flux measurement system.
- A cold-mix paver can successfully apply an admix containing cationic asphalt emulsion and concrete sand with a residual asphalt content of 23 wt%.
- A soil stabilizer can apply a cationic asphalt emulsion directly to the tailings for stabilization (~5 wt% asphalt) or sealing (~22 wt% asphalt). However, the variation in particle size distribution from site to site has a significant effect on the effectiveness of this technique.
- The chemical and physical properties of the radon barrier system are such that it should endure for a long time period.
- Maintaining overburden over the seal is important in maintaining the long-term integrity of the seal.

## RECOMMENDATIONS

The FY-1980 program was successful in that it further demonstrated that uranium tailings can be radon sealed in the field. The laboratory and field studies and, in particular, the 1980 Grand Junction field test provided a considerable amount of valuable information. Based on this information the following recommendations are made for improving the FY-1981 program.

### LABORATORY STUDIES

- Determine physical-chemical characteristics of the seal aggregate, such as size distribution, surface area, zeta potential, and chemical makeup, to optimize seal formulation.
- Determine the characteristics of the asphalt emulsion, such as emulsion type, zeta potential and asphalt source, that will help optimize seal formulation.
- Carry out an extensive effort to evaluate the long-term stability of the seal (see Appendix B for detailed research plan).
- Continue to improve the radon diffusion test apparatus and determine effective diffusion coefficients for the admix seals.
- Investigate the use of rubberized asphalt as a radon seal.

### FIELD STUDIES

- Continue to review application technology to identify cost-effective techniques most applicable to the sealing system. Identify modifications to equipment. Continue equipment screening tests on the more promising application equipment.
- Further improve and test the radon field flux measurement system, and compare it to other flux measurement systems.
- Include a total characterization of the test site to identify how the tailings interact with the seal. This should include a carefully designed geochemical and hydrological analysis of the tailings below the seal.

- Carry out a comparative field test to determine the relative effectiveness and longevity of different radon barrier systems. The systems that should be compared are:
  - asphalt emulsion sealing system
  - multilayer radon barrier
  - soil overburden

  An area of about 1 to 5 acres per system is suggested. As stated earlier the tailings under these systems should be carefully characterized before and after the radon barriers are applied.
- Characterize radon exhalation anomalies if they occur at the edges of the seal system.
- Compare the technical and economic feasibility of the three radon barrier systems and establish basic engineering specifications for use by an architectural and engineering firm.

# LABORATORY STUDIES

The overall objective of the laboratory studies was to investigate various asphalt-emulsion sealing systems to contain radon and other potentially hazardous materials within uranium mill tailings. The major activities included characterizing the uranium tailings and seal aggregate, formulating the seal, measuring radon diffusion, and evaluating the potential long-term stability of the seal.

## URANIUM TAILINGS AND SEAL AGGREGATE CHARACTERIZATION

The physical and chemical properties of the tailings or aggregate are important in determining the life of the seal. Therefore, we selected and analyzed samples of tailings from the inactive sites and samples of candidate seal aggregates such as concrete sand.

Particle size distribution of the seal aggregate is an important parameter in forming a gas-tight seal. It has an affect on the ability of the emulsion to mix with the tailings and on the integrity of the seal. When a major part of the aggregate has a large surface area per unit volume--below 200 mesh (silt or clay)--it is very difficult to obtain a good seal. Therefore, if tailings are to be used as the seal aggregate they must not contain a significant amount of fines below 200 mesh (e.g., 20%). To illustrate this potential problem, Figure 2 shows the wide variation in particle size distribution of the uranium tailings from selected sites. The effect of this variation on formulating a seal is discussed in the following section on seal formulation.

Because of the problems in using tailings as the seal aggregate, other sources of aggregate were considered such as a local blowsand, crushed rock, and concrete sand. The blowsand available near a tailings site may be the most promising source of aggregate, but, since it will probably vary significantly from site to site, we chose to use concrete sand as our standard aggregate for seal formulation. Crushed rock usually contained too much coarse material (+0.6 cm) to provide an adequate seal.

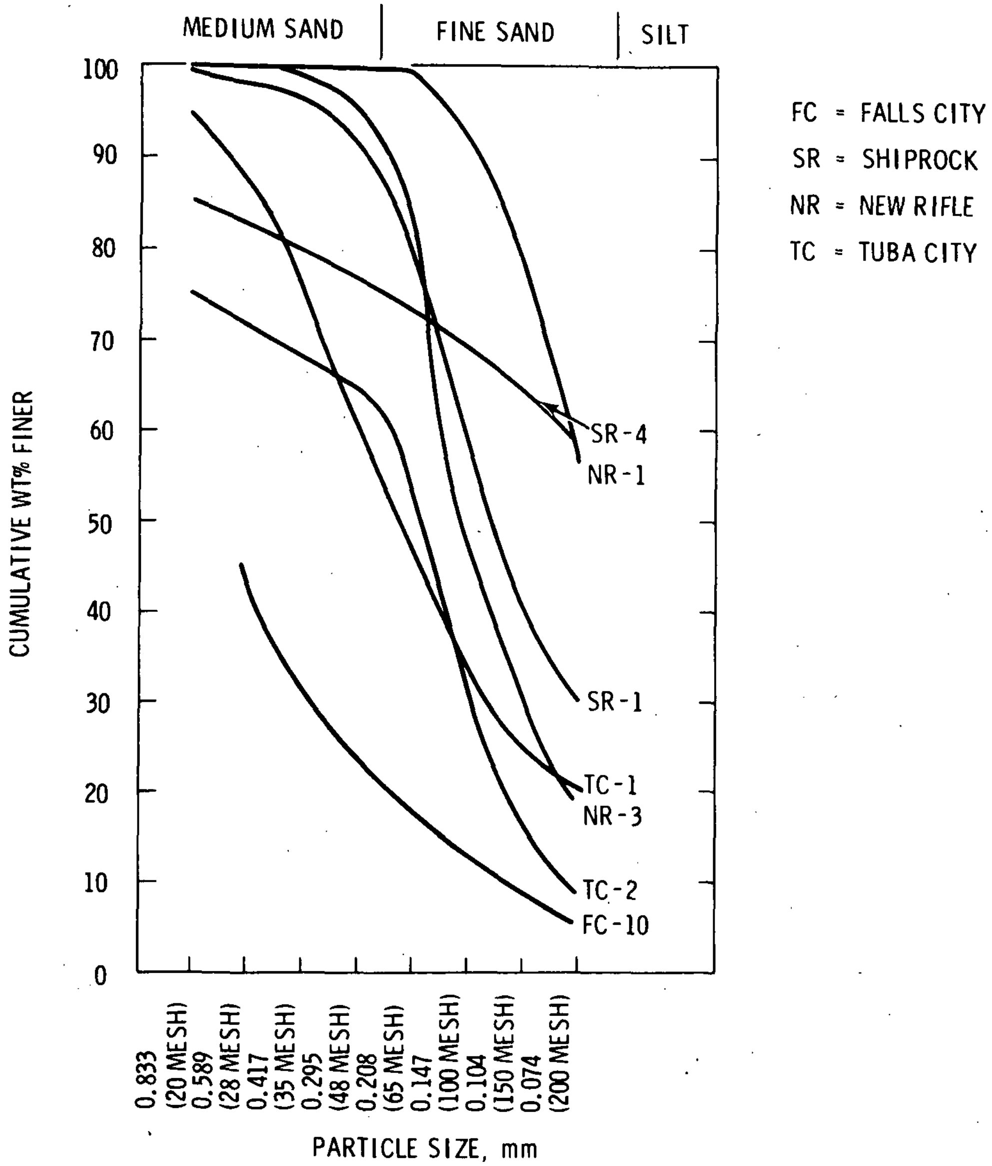


FIGURE 2. Variations in Particle Size Distribution of Uranium Tailings From Selected Sites

Since concrete sand was selected as the standard aggregate for both laboratory and field studies, samples were obtained from Grand Junction, Colorado. Also, samples of the tailings in the test plot selected for the 1980 field test were obtained. Figure 3 compares the size distribution of the tailings in this test plot to the size distribution of Grand Junction concrete sands selected for the field test.

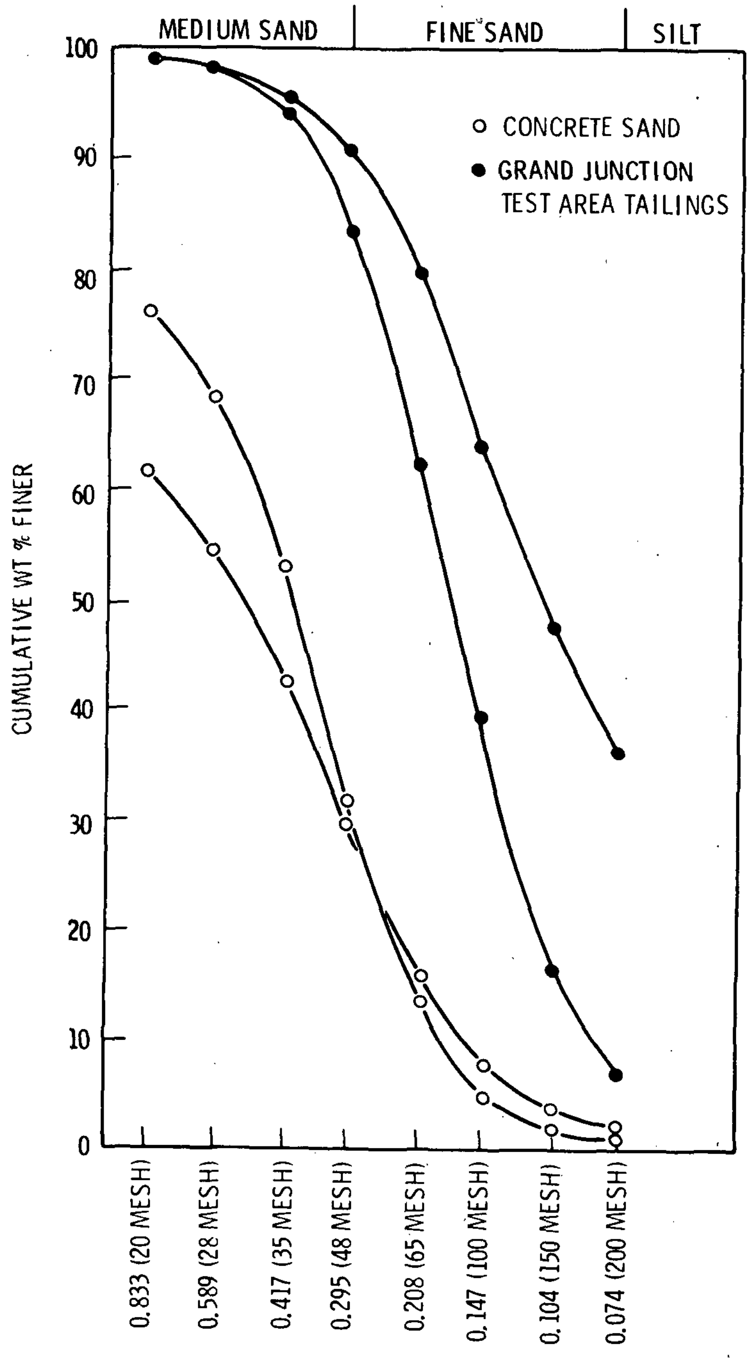


FIGURE 3. Variations in Particle Size Distribution of Grand Junction Tailings in Test Area and Local Concrete Sand

The chemical composition of the tailings is also important, particularly if tailings are to be used as a seal aggregate. The chemical composition of the Grand Junction tailings in the 1980 test area are shown in Table 1. However, of special interest are any precipitated salts that occur with the tailings, such as water-soluble salts. An example of the water-soluble salts in the Grand Junction tailings is shown in Table 2.

TABLE 1. Chemical Composition of Grand Junction Tailings in Field Test Area[(a)]

| Element | Composition, ppm Range | Average |
| --- | --- | --- |
| K[(b)] | 0.26 - 0.57 | 0.45 |
| Ca[(b)] | 0.26 - 1.13 | 0.73 |
| Ti | 122 - 857 | 450 |
| V | 889 - 4066 | 1457 |
| Cr | 38 - 155 | 61 |
| Mn | 14 - 65 | 35 |
| Fe[(b)] | 0.15 - 1.00 | 0.39 |
| Cu | 11 - 42 | 25 |
| Zn | 65 - 178 | 119 |
| Se | 22 - 77 | 54 |
| As | 6.8 - 100 | 43 |
| Rb | 7.8 - 17 | 13 |
| U | 38 - 848 | 130 |
| Sr | 31 - 215 | 94 |
| Y | 2.5 - 15 | 8.7 |
| Zr | 113 - 340 | 220 |
| Nb | 0.9 - 3.2 | 2.1 |
| Mo | 15 - 34 | 26 |
| Ra[(c)] | 34 - 1730 | 361 |

(a) Data obtained by X-ray fluorescence analysis.
(b) Given in %.
(c) Radium content determined by direct counting; given in pCi/g.

TABLE 2. Water-Soluble Salts in Grand Junction Tailings Test Area

| Cation[a] | Sand Samples, ppm GJ-80-1 | Sand Samples, ppm GJ-80-4 | Slimes Samples, ppm GJ-80-2 | Slimes Samples, ppm GJ-80-3 |
|---|---|---|---|---|
| Al | 0.45 | 0.70 | 4.00 | 2.80 |
| As | 1.25 | 1.65 | 4.40 | 3.60 |
| Ba | 0.15 | 0.20 | 0.20 | 0.15 |
| Ca | 3200. | 3050. | 3550. | 3450. |
| Cd | D.L. | 0.03 | 0.05 | 0.15 |
| Ce | 0.40 | 0.25 | 0.25 | 0.40 |
| Co | 2.00 | 0.55 | 0.50 | 0.05 |
| Cr | 0.05 | 0.05 | 0.10 | 0.10 |
| Cu | 0.05 | 0.25 | 0.25 | 1.15 |
| Fe | 0.05 | 0.25 | 0.15 | 0.20 |
| Gd | 0.20 | 0.15 | 0.20 | 0.30 |
| K | 12.00 | 13.00 | 60.00 | 120.0 |
| La | 6.00 | 5.00 | 6.50 | 6.00 |
| Li | 0.25 | 0.50 | 0.50 | 1.00 |
| Mg | 150.0 | 90.00 | 360.0 | 260.0 |
| Mn | 0.30 | 0.35 | 2.05 | 2.55 |
| Mo | 1.45 | 2.50 | 8.50 | 3.70 |
| Na | 220.0 | 140.0 | 700.0 | 650.0 |
| Nd | 0.70 | 0.75 | 0.55 | 0.95 |
| Ni | 1.40 | 0.35 | 0.60 | 0.30 |
| P | 1.25 | 0.80 | 0.75 | 7.00 |
| Si | 75.00 | 60.00 | 85.00 | 50.00 |
| Sr | 16.00 | 14.50 | 17.50 | 18.00 |
| Te | 6.00 | 5.50 | 60.00 | 28.50 |
| Zn | 1.00 | 0.90 | 1.00 | 1.15 |
| **Anion[b]** | | | | |
| $SO_4$ | 7400 | 7100 | 7400 | 7500 |
| $Cl^-$ | 475 | 290 | 1650 | 1350 |
| $NO_3$ | 85 | 150 | 1175 | 1170 |
| $F^-$ | 6 | 10 | 8 | 10 |
| $PO_4$ | 5 | 5 | 5 | 5 |

(a) Data obtained by induction-coupled plasma spectrometry (ICP) analysis.
(b) Data obtained by ion chromatography (IC) analysis.

In order to further understand the chemical and physical properties of the tailings, selected samples of Grand Junction tailings were examined using a scanning electron microscope (SEM) with an attached x-ray dispersive microprobe. Figure 4 shows the typical particle characteristics and mineralogy of a selected tailings sample from the Grand Junction tailings pile.

In support of the Grand Junction field test, standard soil physical characterization tests were performed in selected locations of the test area. Both the silty clay cover material and the tailings below were tested. A summary of results is presented in Table 3. Details of the tests are presented in Appendix C.

## SEAL FORMULATION

Previous testing (Hartley et al. 1980, 1977) has shown that a simple poured-on or sprayed-on seal application technique would provide a radon barrier but would not be able to withstand mechanical forces associated with overburden installation. Overburden is required for seal protection from

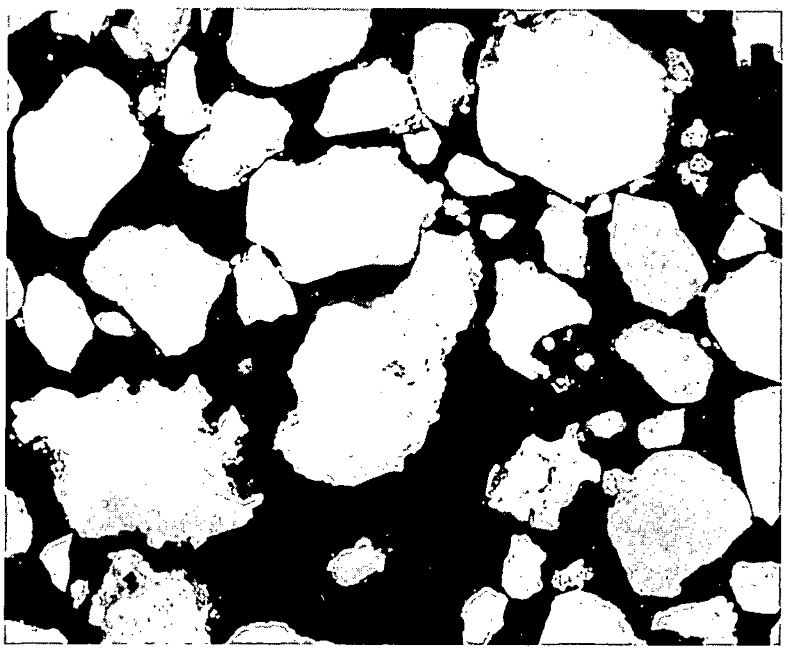

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FIGURE 4. Photomicrograph of Typical Grand Junction Sandy Tailings

TABLE 3. Summary of Selected Physical Characteristics of Grand Junction Overburden and Tailings in Field Test Area

| | Silty Clay Overburden 0 to 6 in. deep | Maroon Tailings 6 to 18. deep | Tan Tailings 6 to 18 in. deep |
|---|---|---|---|
| Liquid Limit, LL (Atterberg Limits) | 38.5 | NP(a) | NP |
| Plasticity Index, PI (Atterberg Limits) | 17.3 | NP | NP |
| California Bearing Ratio, CBR | 2 at 96.6% optimum density (modified proctor) | 3 at 96.7% optimum density (modified proctor) | 12 at 96% optimum density (modified proctor) |
| Classification(b) | CL | SM or SC | sand |
| Swell, % | 6.3 at 111.6 $lb/ft^3$ dry density | 0.1 at 105.2 $lb/ft^3$ dry density | 1.7 at 99 $lb/ft^3$ dry density |
| Optimum dry density, $lb/ft^3$ | 115.5 | 108.7 | 102.8 |
| Optimum moisture, % | 15.1 | 12.6 | 10.8 |

(a) NP - not possible
(b) Unified Soil Classification System. Adopted by U.S. Army Corp. of Engineers and Bureau of Reclamation, January 1952.

ultra-violet radiation, oxygen/ozone attack, and wind and water erosion. In fact, to extend the life of the seal a substantial overburden thickness creating a near anaerobic condition adjacent to seal surface is needed. Tests on admixtures 5 to 8 cm thick were conducted in the laboratory to simulate expected field installation thicknesses. Field seals containing approximately 22 to 25 wt% residual asphalt[a] and 5 to 8 cm thick were believed to be adequate to withstand forces exerted by equipment during overburden installation as well as animal and root penetrations. In case of minor subsidence this thickness range was thought to be near the most effective thickness for healing seal fractures.

(a) Based upon industry standard of dry aggregate basis, i.e., wt. asphalt/wt aggregate.

Many variables are involved in seal fabrication and resultant seal quality. The more important were investigated in the laboratory prior to selecting a final emulsion and aggregate types for subsequent field testing. These variables include 1) mix design and test procedure, 2) effect of aggregate type, 3) effect of emulsifier type and asphalt concentration, 4) effect of asphalt source, 5) effect of herbicide addition, and 6) effect of mixing variables on admixture characteristics. After reviewing results of the laboratory seal formulation studies, field test recommendations were made.

Mix Design and Test Procedure

The laboratory analyses were designed to duplicate the field tests during seal installation and subsequent environmental exposure. All laboratory specimens were prepared and tested in a manner as close to field studies as possible. The mix design test procedure consisted of the following steps:

1) The selected seal aggregate was dried and weighed. Water was added to bring aggregate moisture to an optimum moisture content (Hartley et al. 1980) and mixed with aggregate for 2 to 5 min in a laboratory mixer (Soil Test Model C110) (see Figure 5). Asphalt emulsion necessary to obtain the specified residual asphalt was then added and mixed for 30 s at the lowest speed. All ingredients were at ambient temperature unless temperature was a specific variable.

2) Immediately after mixing, the admixture was transferred to a sloping metal tray for 24 h to drain and dry.

3) The admixture was then transferred to a compaction mold lined with paper towels on all surfaces to facilitate drainage (see Figure 6). In the field, compaction after admix application would most likely occur several weeks apart. In addition, field dehydration surface temperatures were expected to exceed 49°C (120°F) during the day compared to 22°C (72°F) under laboratory conditions.

4) The admixture was compacted at 551 kPa (80 psi), relaxed after 20 s, and recompacted again at 551 kPa for 10 s. The extruded specimen was placed in an open hood for 4 h of drying. A typical test specimen is shown in Figure 7. The 551-kPa value was derived by two methods. A

FIGURE 5. Laboratory Mixer Used to Prepare Admix

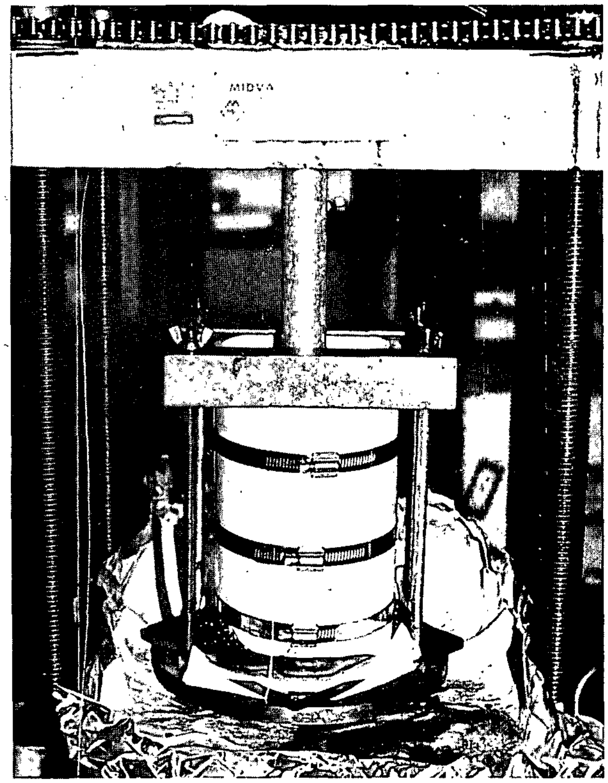


FIGURE 6. Compaction Mold Used to Prepare Test Specimens

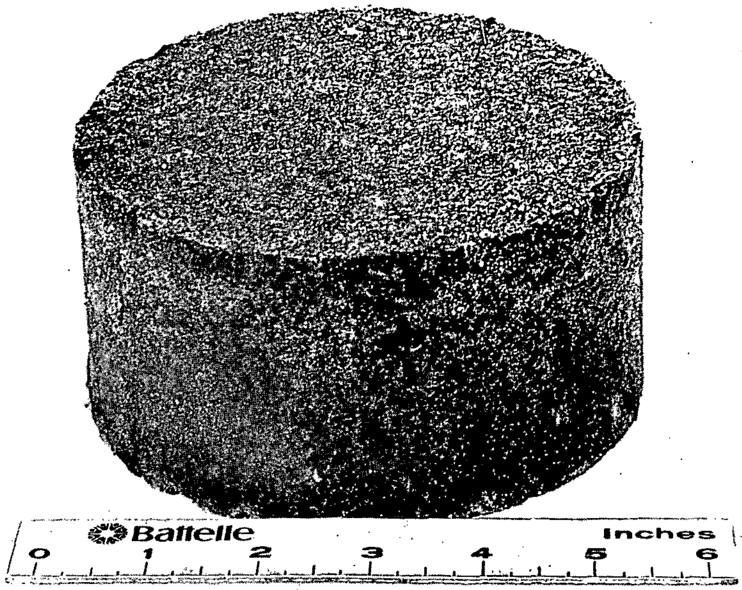



FIGURE 7. Typical Asphalt Emulsion Seal Test Specimen

20-t vibratory roller has a 2.4-m wide roller of which 15.2 cm is in contact with seal surface. This calculates to about 551 kPa pressure in the vibratory mode of operation.

5) The specimen sides were coated with the test emulsion and allowed to air dry in an open hood for 24 h. The test specimen was checked for slumping or deformation. If the specimen held up, it was used in the following steps.

6) The specimen was placed on top of a porous media, such as coarse sand, and molten asphalt was poured between the specimen and test cell wall to effect gas-tight sealing. Entrapped air bubbles were surfaced by external heating with a laboratory forced-air heater (hair dryer). A typical mounted specimen in the test cell is shown in Figure 8.

7) Next the specimen was tested for major leaks using a helium leak test procedure. The seal was covered with 1.5 to 3.0 cm water, and a helium pressure of 3.5 kPa was exerted below the seal for about

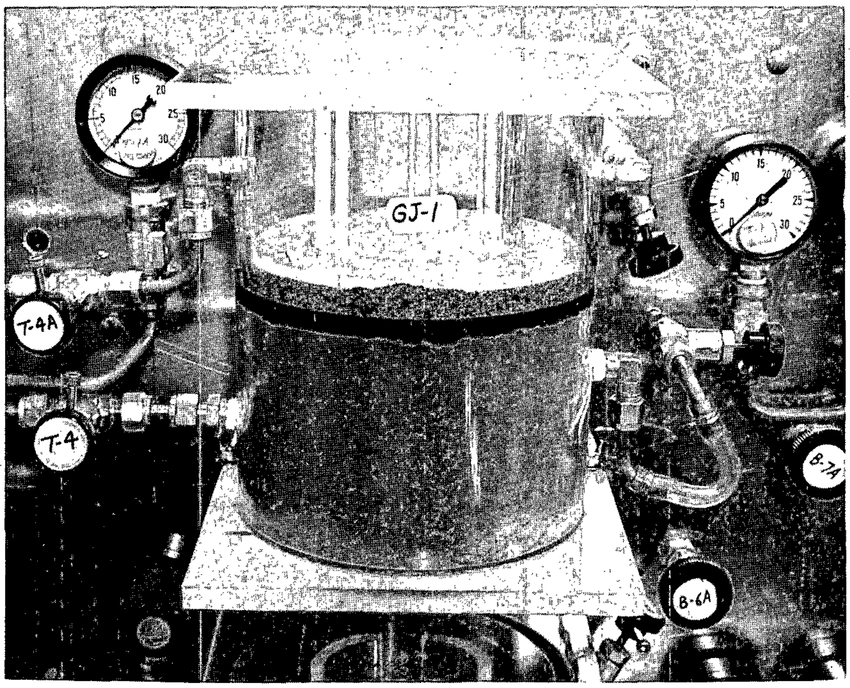



FIGURE 8. Test Cell Used to Evaluate Effectiveness of Seal

30 min. If bubbling was observed from the specimen's upper surface area, the test was terminated and the specimen termed a failure. If bubbling occurred within the hot asphalt cement seal, it was repaired and retested. Previous experience has shown that any specimen failing the helium pressure test always immediately failed the subsequent pressurized radon test. On the other hand, any specimen passing the helium pressure test may or may not pass the pressurized radon test. In fact, in tests 11, 13, and 28 the seal had passed the helium pressure test and failed later in the longer-term radon pressure test at a lower pressure (see Appendix A).

8) The test specimens passing the helium leak test were then tested using the radon test apparatus (see section on Laboratory Radon Diffusion Measurements).

## Effect of Aggregate Type On Seal Quality

It was initially planned to use on-site tailings as the seal aggregate source if technically feasible. All test samples prepared using tailings from sites at Vitro-Salt Lake City, Utah; Ambrosia Lake, New Mexico; and Grand Junction, Colorado, formed radon-impervious seals using low zeta potential (less than +18 mV) cationic asphalt emulsions. Residual asphalt content ranged from 22 to 25 wt% in these seals. As seal formation testing continued using samples taken from Shiprock, New Mexico, and Tuba City, Arizona, more and more seal failures occurred during testing (Tests 3-16).

Finally with the Tuba City, Arizona, samples (Tests 17 and 18) and the New Rifle, Colorado, samples (Tests 22-24) it was concluded that a long-term, stable, radon-impervious seal could not be made from tailings with such a high silt content. Even with an emulsion designed to coat fine aggregates and with as much as 37.7 wt% residual asphalt, a seal could not be made. A search for equipment to economically remove the fines from tailings was unsuccessful.

If tailings with the desired size distribution are unavailable, then a second low-cost alternative for the aggregate might be a local blowsand. For this reason Hanford blowsand (Test 21) and -10 mesh Hanford blowsand (Tests 29, 41, 42, 44-49, 52, 54, 129-135) were used as the aggregate test media. In some tests, Hanford blowsand was sieved and its size distribution adjusted to compare with sandy Grand Junction, Colorado, tailings (Tests 28, 30, 38, 43). The Hanford blowsand (Test 21), the -10 mesh fraction of Hanford blowsand (Tests 29, 43-48, 52, 53, 129-135), and the Grand Junction size distribution Hanford blowsand (Test 30) aggregate sources all produced good quality seal test specimens using Armak 4868, Chevron QS-h, Chevron CSS, and Armak +78 mV type cationic asphalt emulsions. Residual asphalt content must be at least 18 wt% and preferably a minimum of 22 wt% for use with blowsands. Above 25 wt% slumping at room temperature is excessive. The use of blowsand, the primary aggregate, was curtailed when it was discovered 1) not every site has a nearby blowsand source, and 2) size distribution and clay contaminants would probably require a washing-sizing operation prior to use. Removal of troublesome -200 mesh particles from blowsand in needed quantities may not be cost effective.

Standards on concrete sand have established a particle size range limitation that is duplicated throughout the United States (see Table 4). Use of concrete sand as the aggregate media standardizes the size range, but size distribution within that range can vary considerably. In general, concrete sand

TABLE 4. Size Specification for Concrete Sand

| Range, wt% | | Sieve Designation |
|---|---|---|
| 90 to 100 | passes | #4 mesh (4.75 mm) |
| 45 to 75 | passes | #16 mesh (1.18 mm) |
| 25 to 55 | passes | #36 mesh (485 μm) |
| 5 to 30 | passes | #50 mesh (300 μm) |
| 0 to 8 | passes | #100 mesh (150 μm) |

is coarser than blowsand. The three sources of concrete sand used in the seal formulation studies were United, Inc., and Whitewater, Inc., both in Grand Junction, Colorado, and the J. A. Jones concrete plant on the Hanford project. The majority of all specimens were prepared from these aggregates (local concrete sand--45 tests, United concrete sand--21 tests, and Whitewater concrete sand--10 tests). In addition to variable size distribution within the allowable size range a considerable difference in particle coating was noted. The United concrete sand, for example, reacts more rapidly and coats better than the Whitewater concrete sand which in turn is an improvement over the local sand. It is not known how representative the Grand Junction concrete sand samples are that were received at PNL. Both companies, Whitewater and United, frequently change aggregate sources during the year. A pure quartz sand has a very low zeta potential and should be avoided as an aggregate source. The use of concrete sand as the preferred aggregate forced a change in the asphalt emulsion to be used for seal formulation. The zeta potential range of the emulsion needed to be changed from a low to medium category. This will be discussed in a subsequent section.

Some crushed rock aggregates were tested (Tests 31-37) with partial success. The primary difficulty was an inability to totally fill the void volume between aggregate particles with asphalt, vital for radon seal integrity. A sized crushed aggregate mixture with minimal void volume may have been satisfactory; however, it was not available. Additional studies of coarser aggregates should be made for applications to slumping problems on slope seal applications.

Effect of Emulsified Asphalt Type and Concentration

Asphalt emulsions of interest in this application must be cationic to be able to electrostatically bond to the negatively charged aggregate. The average charge intensity of the asphalt droplet then arbitrarily places the emulsion into one of three broad categories, i.e., cationic slow set (CSS), cationic medium set (CMS), and cationic rapid set (CRS). Most of the asphalt emulsion manufacturers do not use the zeta potential (asphalt droplet charge intensity) as the method of categorizing the emulsion; instead they decide by observing the rate of reaction of the emulsion with the aggregate. Zeta potential classification of emulsion helps provide control during mix design. For example, an asphalt emulsion can be prepared at a specific zeta potential to match a specific aggregate, thus helping to optimize mixing.

Some emulsion manufacturers specialize in emulsions that contain 2 to 20 wt% solvent (usually a high-boiling point naptha). Solvent-containing emulsions are usually designated with a -2. For example, CMS-2 is a cationic medium set emulsion containing solvent. The solvent greatly improves aggregate coating which is important in highway installation and this application. Volatility rates that can be expected over a long-term (such as 1000 years) stability period are unknown. It is also not known whether the void remaining upon volatilization will cold flow into a radon-tight seal. A potentially more serious problem is slumping. Severe slumping was observed on Tests 68, 76-78 which suggests a potentially severe problem in meeting long-term stability requirements on sites where a maximum slope of 20% is utilized. For these reasons no further tests with solvent-containing emulsions were conducted.

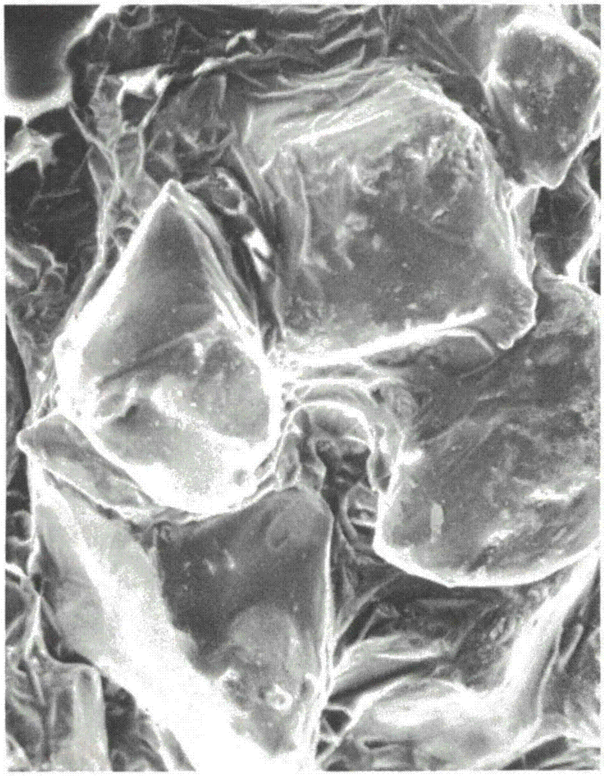
As a general rule, a low zeta (CSS) emulsion is selected for fine aggregates, medium zeta (CMS) emulsion for coarser aggregate (for example, concrete sand), and high zeta (CRS) emulsion for very coarse aggregate. Not all asphalt emulsion manufacturers have the facilities to prepare small quantities (19 to 38 L) of all emulsions. This is one reason why some of the leading emulsion manufacturers' products were not tested for this application. In addition, few emulsion manufacturers were willing to prepare minor field test quantities (up to 11,355 L) for equipment screening tests. Emulsions investigated during FY80 are listed as follows.

| CSS | CMS | CRS |
|---|---|---|
| Armak 4868 | Armak +54 mV | Armak +93 mV |
| Chevron C55-1 | Armak +56 mV | Chevron QS-h |
| Chevron 79R3416 | Armak +62 mV | Chevron QS-K-h |
| | Armak +78 mV | |
| | Chevron CMS-2 | |
| | Union 76 CMS | |
| | US Oil CMS-2 | |

The residual asphalt content, necessary to seal radon, varied with aggregate size. For most of the tailing samples a 22- to 25-wt% residual asphalt content was adequate for sealing. For tailings with size distribution largely +100 mesh sealing at about 22 wt% residual asphalt could be expected. As the fines content increases, a higher asphalt content, e.g., 25 wt%, must be used. However, if the fines content is too great, even an increased content of asphalt will not produce an adequate seal. For example, 37.7 wt% asphalt (Test 23) failed to effect a seal. The concrete sands were readily sealed by using 22 to 23 wt% asphalt. Sealing concrete sand is considerably more difficult using a CSS as opposed to a CMS. Once the decision was made to use concrete sand as the aggregate for the field test, the investigation narrowed as to which CMS emulsion was preferred and its nearest source. To examine the ability of the more promising emulsions to properly coat the aggregate, sample seals were prepared and examined with a scanning electron microscope (SEM). Figure 9 shows good particle coverage using Armak CMS +78 mV and +56 mV asphalt emulsions on concrete sand.

Effect of Asphalt Source

Up until a few years ago, only a few asphalt sources were suitable for asphalt emulsions. With improved emulsifiers, more asphalt sources could be used, but differences in bonding to paving aggregates became more of a problem. The problem was attributed to base asphalts that were too agglomerated. Dispersants have been developed that have converted nonusable base asphalts into asphalts suitable for emulsion manufacturing. In radon seal applications most of the Armak sample emulsions were fabricated from a Smackover crude source in



100 X

300 X

FIGURE 9. Photomicrographs of Asphalt Emulsion Admix Seals Showing Particle Coating

Arkansas--a known, high-quality asphalt. Asphalt sources used to fabricate other seals are not known. This information is difficult to obtain from manufacturers.

It was decided to select one emulsifier (Armak 4868) and fabricate asphalt emulsions from five different base asphalts, including treated asphalts, to determine if a variety of base asphalts could be used (see Table 5). Of particular interest are the treated asphalts which, if used, would mean a large majority of the world's asphalt sources are usable in this application. The asphalt emulsions were prepared by Armak. The results of testing the five base asphalts are presented in Table 6.

TABLE 5. Asphalt Sources Used to Produce Emulsions #1 Through #5

| Asphalt Emulsion[a] | Asphalt Source | Comments |
|---|---|---|
| Armak 4868 #1 | Edgington, CA | untreated |
| Armak 4868 #1 | Lion (Smackover Crude), AK | chemically treated |
| Armak 4868 #3 | Lion (Smackover Crude), AK | untreated |
| Armak 4868 #4 | Oklahoma City, OK | chemically treated |
| Armak 4868 #5 | Oklahoma City, OK | untreated |

(a) Fabricated for PNL by Armak Co., 8401 W. 47th Street, McCook, IL.

The following conclusions are based on the information gathered from evaluating these asphalts:

- All specimens prepared with Armak 4868 #1 did not pass the helium leak test and were, therefore, unsatisfactory. This material provides extremely poor bonds. In subsequent discussion of results, J. N. Dybalski of Armak, Co. stated that the asphalt in 4868 #1 was generally considered unsuitable for asphalt paving or other asphalt emulsion applications but was included for comparison.
- Specimens prepared with Armak 4868 #2, #3, #4 and #5 showed no significant differences in ability to form radon seals.
- Specimens prepared with Armak 4868 #2, #3, #4, and #5 are best suited for fine aggregates such as -10 Hanford blowsand.
- Specimens prepared with Armak 4868 #2, #3, #4, and #5 are unsuitable with local or United Concrete sand at residual asphalt concentrations less than 20 wt%.
- Specimens prepared with Armak 4868 #2, #3, #4, #5 provide good candidate seal material when the emulsion is heated to 32$^{\circ}$C to 38$^{\circ}$C before mixing.
- Specimens prepared with Armak 4868 #2, #3, #4, #5 provide good seal material if compacted when warm.
- Candidate aggregates and emulsions should be tested at expected emulsion arrival temperature and the dehydrated seal material should be compacted when warm.

TABLE 6. Effect of Asphalt Source on Seal Quality

| Test No.[a] | Armak 4868 No. | Aggregate Type | Asphalt Emulsion Temp., $^{o}F$ | wt% Asphalt | Comments |
|---|---|---|---|---|---|
| 54 | 1 | United | 70 | 25.8 | specimen failed - cracked |
| 55 | 2 | United | 70 | 25.8 | specimen excellent 98.9% radon seal |
| 56 | 3 | United | 70 | 25.8 | specimen excellent 99.99% radon seal |
| 57 | 4 | United | 70 | 25.8 | specimen excellent 99.99% radon seal |
| 58 | 5 | United | 70 | 25.8 | specimen excellent 99.99% radon seal |
| 59 | 1 | United | 70 | 25.8 | specimen failed He test |
| 96 | 1 | Local | 125 | 25.8 | liquid-sand separation severe |
| 97 | 2 | Local | 125 | 25.8 | liquid-sand separation - discarded |
| 98 | 3 | Local | 125 | 25.8 | liquid-sand separation - discarded |
| 99 | 4 | Local | 125 | 25.8 | liquid-sand separation - discarded |
| 100 | 5 | Local | 125 | 25.8 | liquid-sand separation - discarded |
| 101 | 1 | Local | 70 | 25.8 | slow 3-step emulsion addition, sand-liquid separation severe, discard |
| 102 | 2 | Local | 70 | 25.8 | slow 3-step emulsion addition, sand-liquid separation, discard |
| 103 | 3 | Local | 70 | 25.8 | slow 3-step emulsion addition, sand-liquid separation, discard |

TABLE 6. contd

| Test No.[(a)] | Armak 4868 No. | Aggregate Type | Asphalt Emulsion Temp., $^oF$ | wt% Asphalt | Comments |
|---|---|---|---|---|---|
| 104 | 4 | Local | 70 | 25.8 | slow 3-step emulsion addition, sand-liquid separation, discard |
| 105 | 5 | Local | 70 | 25.8 | slow 3-step emulsion addition, sand-liquid separation, discard |
| 107 | 1 | Local | 70 | 21.4 | specimen has obvious voids |
| 108 | 2 | Local | 70 | 21.4 | specimen fell apart |
| 109 | 3 | Local | 70 | 21.4 | specimen appears asphalt-deficient |
| 110 | 4 | Local | 70 | 21.4 | specimen appears good |
| 111 | 5 | Local | 70 | 21.4 | excellent specimen |
| 114 | 1 | Local | 90 | 22.7 | good specimen |
| 115 | 1 | Local | 90 | 25.1 | excellent specimen |
| 116 | 2 | Local | 90 | 22.7 | good specimen |
| 117 | 2 | Local | 90 | 25.1 | excellent specimen |
| 118 | 3 | Local | 90 | 22.7 | good specimen passed He test |
| 119 | 3 | Local | 90 | 25.1 | excellent specimen |
| 120 | 4 | Local | 90 | 22.7 | good specimen |
| 121 | 4 | Local | 90 | 25.1 | excellent specimen |
| 122 | 5 | Local | 90 | 22.7 | good specimen |
| 123 | 5 | Local | 90 | 25.0 | excellent specimen |
| 129 | 2 | -10 Hanford blowsand | 110 | 22.0 | compacted at 90$^oF$ excellent specimen |
| 130 | 3 | -10 Hanford blowsand | 110 | 22.0 | compacted at 90oF excellent specimen |

TABLE 6. contd

| Test No.[a] | Armak 4868 No. | Aggregate Type | Asphalt Emulsion Temp., °F | wt% Asphalt | Comments |
|---|---|---|---|---|---|
| 131 | 4 | -10 Hanford blowsand | 110 | 22.0 | compacted at 90°F good specimen |
| 132 | 5 | -10 Hanford blowsand | 110 | 21.9 | compacted at 90°F good specimen |
| 134 | 2 | -10 Hanford blowsand | 70 | 22.0 | compacted at 90°F excellent specimen |
| 135 | 3 | -10 Hanford blowsand | 70 | 22.0 | compacted at 90°F excellent specimen |
| 136 | 4 | -10 Hanford blowsand | 70 | 22.0 | compacted at 90°F excellent specimen |
| 137 | 5 | -10 Hanford blowsand | 70 | 22.0 | compacted at °F excellent specimen |

(a) See Appendix A

## Effect of Herbicide Addition

Treflan® effectiveness as a long-term biological barrier is being investigated in another UMTRAP-sponsored project at PNL. Test seals were fabricated from known compatible emulsion-aggregate combinations with three Treflan® concentrations, and radon permeation data were obtained as shown in Table 7. Based on appearance and limited test data it does not appear that Treflan® has any deleterious effect on seal quality at concentrations up to 40 lb/acre (22 g/m$^2$).

## Effect of Mixing Variables on Admixture Characteristics

Other important variables that can have a significant effect on the seal formulation and quality are emulsion temperature, mix time, admixture

® Treflan is a registered trademark of Elanco, Co.

TABLE 7. Effect of Treflan® on Seal Quality

| Test No.[a] | Aggregate Type, °F | Treflan® lb/acre | Emulsion Type | wt% Asphalt | He Test | Test Duration, h | % Flux Reduction |
|---|---|---|---|---|---|---|---|
| 44 | -10 Hanford blowsand | 0 | Armak 4868 | 19.7 | passed | 72 | 99.96 |
| 45 | -10 Hanford blowsand | 1.5 | Armak 4868 | 19.7 | passed | 72 | 99.99 |
| 46 | -10 Hanford blowsand | 10 | Armak 4868 | 19.7 | passed | 73 | 99.29 |
| 47 | -10 Hanford blowsand | 40 | Armak 4868 | 19.7 | passed | 73 | 99.97 |

(a) See Appendix A.

fluidity, admixture compaction, and compaction temperature. Each of these variables may influence seal quality as much as emulsion and aggregate selection.

Elevated emulsion temperature not only accelerates the reaction between aggregate and emulsion but it also results in an admixture considerably more fluid than at ambient conditions. This can be a potentially serious problem on slopes where water flow may occur. This fluidity also must be considered in selecting the application equipment. To observe the effect of temperature upon reaction rates and admixture fluidity, several emulsions with different zeta potential were mixed with concrete sand at different temperatures as shown in Table 8. (Appendix A gives more details.)

Temperatures of stockpiled aggregates are not expected to be much of a factor with summer heat. Evaporative cooling of entrained water is expected to keep aggregate interior temperatures below 29°C (85°F). If an extended abnormally cool period were to occur, a profound effect is expected particularly on the admixture flow characteristics. Increasing the emulsion temperature is probably the simplest remedy for maintaining proper mixing/placement admixture characteristics.

TABLE 8. Asphalt-Emulsion Concrete Sand Mix Tests at Different Emulsion Temperatures

| | Test No. in Appendix A | | | | |
|---|---|---|---|---|---|
| Temperature, °F | Armak+54 mV | Armak+56 mV | Armak+62 mV | Armak+78 m | Armak+93 mV |
| 70 | 91,25 | 64,65,69, 92,106,112, 113,124, | 126 | 67,70,127, 133,139 | |
| 110 | | 128 | | | |
| 120 | 84 | 72,74 | 85 | 71,73 | 86 |
| 125 | 87 | 80,81,83 | 88,90,93 | 94 | 89,95 |

If the admixture is to be transported any significant distance, it must be mixed en route. This may involve extensive mixing times. It was noted that the Armak +56 mV emulsion, a prime candidate, foamed much more than other emulsions. Lengthy mixing times resulted in excessive foam formation (Tests 66 and 75).[a] Attempts to reduce foaming to tolerable levels by adding antifoaming agents (Test 79)[a] failed. Changing emulsifiers to produce an emulsion of comparable zeta potential (+54 mV) resulted in similar performance with tolerable foam formation (Test 84)[a] even at 49°C emulsion temperature. All other emulsions tested did not generate excessive foaming regardless of mixing temperature.

In an attempt to obtain a cationic emulsion of about +67 mV, Armak +56 mV and Armak +78 mV were mixed together (Test 82). The resultant specimen appeared excellent but failed the pressurized helium test. According to J. N. Dybalski of Armak, emulsifiers usually can be combined prior to emulsification, but combining two emulsified asphalts is seldom successful.

One of the most important variables in the radon seal system is compaction. Premature compaction results in trapped water in the seal which can subsequently provide radon pathways (partial or complete) by evaporation or crack-drainage loss. Available moisture measurement devices can determine minimum admixture moisture levels for optimum compaction. The admixture seal

(a) See Appendix A for test details.

material is a very poor thermal conductor, especially at extremely low moisture content. The admixture radiates heat at night resulting in a cool, stiff material by morning. As the sun's angle of incidence increases, the upper surface of the seal matter becomes soft and pliable. Compaction at this time is quite shallow, such as the first 3 to 5 cm. Deep compaction (5 to 8 cm) will require compaction late in the day, perhaps well into the night.

Another option for resolving compaction problems is to use a softer grade asphalt in emulsion preparation. By the same token, to prevent slumping problems on slopes an emulsion with a harder grade asphalt may be used. Neither of these options was investigated during this study.

Field Test Recommendations

Certain conditions established by time or financial constraints for the field test at Grand Junction, Colorado, included the following.

1) No more than two different asphalt emulsions would be allowed. Some tailings stabilizations would be conducted using cationic asphalt emulsion. Previous experience dictated the use of a CSS-type emulsion for stabilization of the finely divided tailings.

2) The choice of concrete sand would be limited to one source. The only economically feasible sources in Grand Junction were the Whitewater or United Concrete batch plants.

3) The admixture mixing and placement tests run would involve a) cold-mix paver, b) soil stabilizer, c) portable pug mill and paver, and d) concrete transit mix truck and paver.

4) Only one firm could be selected to make batch types of emulsifiers as most emulsion manufacturers have proprietary agreements with emulsifier manufacturers.

Of the two choices of concrete sand, the United concrete sand was preferred because it was more reactive with CMS emulsions, indicating it contained more anionic deposition sites.

Of the emulsions tested, only CMS and CRS were considered for admixtures with the concrete sand. The Chevron QS-K-h and QS-h emulsions as well as the

Armak +93 mV emulsion all reacted entirely too fast and were not recommended. Equipment plugging problems could be anticipated with use of these emulsions in this application. The Chevron CMS-2 and the U.S. Oil CMS-2 were not considered for this application because they contain solvent. The problem with slumping using solvent-containing admixtures was discussed earlier. The Union 76 CMS was not available near Grand Junction. Remaining then was Armak +78 mV, +62 mV, +56 mV, and +54 mV asphalt emulsions. The Armak +62 mV asphalt emulsion was prepared by Armak using a softer asphalt (150 to 200 Pen) and appeared to slump excessively when specimens were placed on a 20% slope. This eliminated the Armak +62 mV from consideration at the time; however, if that emulsion could be prepared commercially using 85 to 100 Pen asphalt or even a harder grade, it may be a possible consideration for future tests. Very little performance difference except for foaming was noted between the Armak +54 mV and Armak +56 mV emulsions; both were prepared with 85 to 100 Pen asphalt. The choice narrowed to Armak +78 mV and either Armak +56 mV or Armak +54 mV. The admixtures prepared by using concrete sand at ambient temperature and emulsion at expected 130°F to 140°F arrival temperatures were considerably different in consistency. The admixture resulting from United concrete sand and Armak +78 mV at 130°F to 140°F with 20 wt% residual asphalt was firmer than the Armak +56 mV or +54 mV, and thus was preferred. Based on the results of equipment screening tests (see Application Technology section), the Armak +78 mV was considered the best choice to use with a cold-mix paver, portable pug mill or transit mixer.

## LABORATORY RADON DIFFUSION MEASUREMENTS

Laboratory radon diffusion measurements were performed to determine the effectiveness of the seal formulation. The apparatus used for the radon diffusion measurement is the same as that reported in the 1979 Annual Report (Hartley et al. 1980). The seal specimen is initially tested for leaks using a helium leak test as outlined in the Seal Formulation section of this report. If it passes this leak test, it is then tested using the radon diffusion test apparatus. A radon generator using a 120-mCi $Ra^{226}$ source supplies a constant 15 µCi $Rn^{222}$/min to the test cells. Nitrogen carries 100 µCi $Rn^{222}$/L under the seal at 75 cc/min. Also, a nitrogen flow of 75 cc/min is passed over the seal to carry any radon that diffuses through the seal to an activated carbon trap held at -78$^{0}$C by a dry ice/alcohol bath. These radon diffusion tests are run for up to 16 days. When the diffusion test is to be terminated, a sample of the radon gas mixture below the seal is collected on activated carbon for 20 min. This carbon canister, along with a carbon canister containing accumulated radon that has passed through the seal, is counted to determine the amount of radon collected in the canister.

The multidimensional NaI gamma-ray spectrometer used at PNL to count the carbon is documented in the 1979 Annual Report (Hartley et al. 1980). Results of the radon diffusion tests were used to determine the effectiveness of the seal formulation and, therefore, are presented in the Seal Formulation section of this report. Example results of laboratory Radon-Diffusion Measurements are presented in Table 9. A complete list of radon diffusion measurements is presented in Appendix A.

## HISTORY OF ASPHALT

Although more common in the Middle East, natural asphalt deposits are located throughout the world. Asphalt is found in minerals such as gilsonite, wurtzlite, and grahamite as well as in such bitumen seepages as the Trinidad asphalt lake (LeMaire 1953). Traces of asphalt have been found in 7000-year-old tools (Marschner and Wright 1978). Asphaltic mortar was extensively used in Mesopotamia and Egypt (Abraham 1945). Biblical references also document the early use of asphalt. Asphalt was used as a water stop between the brick walls of a water reservoir about 3000 BC (Micropaedia 1974). Early man used bitumen as a paving material, wood preservative, sealant, adhesive, and mortar (LeMaire 1953; Marschner 1980). Many artifacts exist today to document the importance of asphalt in early man's technological development.

Marschner and Wright (1978) have studied asphalts from Middle Eastern archeaological sites. Most of the asphalts contain limestone, silicates, and/or feldspars. In general the asphalt cements in the artifacts averaged 60 wt% mineral matter. Comparisons of the artifact bitumen composition with that of the source bitumen indicated an increased asphaltene fraction in the

TABLE 9. Example Results of Laboratory Radon-Diffusion Measurements

| Aggregate | Asphalt Emulsion | Residual Asphalt, wt%[(a)] | Flux Reduction, % |
|---|---|---|---|
| Shiprock Tailings | Armak 4868 | 17.6 | 61.80 |
| Shiprock Tailings | Armak 4868 | 25.0 | 99.97 |
| Tuba City Tailings | Armak 4868 | 25.0 | 98.90 |
| Tuba City Tailings | Armak 4868 | 29.0 | 99.50 |
| New Rifle Tailings | Armak 4868 | 32.3 | Failed He Test |
| New Rifle Tailings | Armak 4868 | 44.5 | Failed He Test |
| New Rifle Tailings | Armak 4868 | 48.1 | Failed He Test |
| Sand | Armak 4868 | 9.3 | Failed He Test |
| Sand | Armak 4868 | 17.6 | 99.98 |
| Sand -28+200 mesh | Armak 4868 | 22.0 | 99.94 |
| -10 mesh Blowsand | Armak 4868 | 22.0 | 99.98 |
| Crushed Rock | Armak 4868 | 13.6 | Failed He Test |
| Crushed Rock | Armak 4868 | 17.6 | 99.97 |
| -10 mesh Blowsand | Chevron 79R-3416 | 22.0 | Failed He Test |
| Concrete Sand | Chevron CSS-1 | 17.6 | Failed He Test |
| Concrete Sand | Armak #2 | 25.8 | 98.9 |
| Concrete Sand | Armak #3 | 25.8 | 99.9 |
| Concrete Sand | Armak #5 | 25.8 | 99.9 |
| Concrete Sand (Sacramento Slurry Seal Test) | Chevron KQS | 22.2 | 99.9 |
| Concrete Sand (Colfax Cold-Mix Paver Test) | Union 76 CMS-1 | 18.6 | 99.9 |

(a) Based on dry aggregate basis: weight of asphalt/weight of aggregate.

artifact bitumen. They concluded "that the terminal product of exposure to the elements is much the same whether it occurs over geologic ages deep underground or over archaelogical millenia near the surface." Their results suggest that a smaller degree of change in the physical properties of asphalt due to oxidative weathering should occur in stiff, high asphaltene asphalts rather than in the softer low asphaltene asphalts. Thus, the millenia time scale required for this conversion to occur may be slow enough to satisfy the 1000-yr radon seal stability requirement.

## SEAL STABILITY

The seal stability and, thus, the effective lifetime of a radon seal is very important. Concerns about seal stability have limited the choice of seal compositions to natural and semi-synthetic materials. A hybrid radon seal technology using an asphalt-emulsion/aggregate admix has been proposed for mill tailings remedial action. The majority of the asphalt produced annually is from petroleum distillate residue (Vind 1967); it can be considered a semi-synthetic material. The aggregate, or crushed rock, is a natural material. This combination of natural and semi-synthetic materials as an integrated system produces a seal with desirable physical properties, cost effectiveness, and an expected long lifetime. Continued research is needed to develop a lifetime prediction for the asphalt admix seal, even though engineering parameters favor longevity.

Experience with the stability of radon barrier systems is minimal at this time. However, several decades of experience have been obtained concerning the stability of asphalt pavements. This experience will provide direction toward assessing the critical areas of asphalt degradation in the radon barrier system.

Sub-base and base construction, pavement voids content, and traffic stresses are critical factors affecting asphalt road stability (Rostron 1963; Vind 1967). Road failure is commonly attributed to poor mix design, inadequate subgrade and base preparation, freeze-thaw cracking, and asphalt fatigue (Rostron 1963; Gotolski, Smith and Roberts 1968; Asphalt Institute 1979a). Poor mix control results in weak asphalt-aggregate bonding; asphalt separation from the aggregate (stripping) can also occur (Asphalt Institute 1979b). Insufficient pavement structural support caused by subgrade and base failure can lead to pavement cracking. Aggregate settling, traffic stress, and frost-susceptible soil can induce early subgrade and base failure. Freeze-thaw cracking is related to the pavement residual water content; temperature induced expansion and contraction of water in the voids creates internal stresses in the pavement. The interconnected voids in asphalt pavement provide access for air and water into the pavement, and the voids content has been related to asphalt fatigue and freeze-thaw cracking (Green, Tolonen and Peters 1976; Van Oort 1956; Vind 1967; Gotolski, Smith and Roberts 1968).

Asphalt fatigue is a gradual viscosity increase (embrittlement) that occurs with time. This embrittlement is generally attributed to oxidative weathering and stress fluidization (thixotropy) (Vind 1967; Gotolski, Smith and Roberts 1968). This loss of ductility makes the asphalt pavement more likely to crack under applied mechanical stress. Transverse pavement cracking is also associated with asphalt fatigue. Microbial oxidation of asphalt has also been implicated in pavement erosion (ZoBell and Molecke 1978, Vind 1967), but climatic factors may affect the extent of attack. Water leaching of asphaltic components from pavements partly depends on the extent of asphalt fatigue (Kleinschmidt and Snoke 1959). Importantly, many factors that adversely affect road performance are either irrelevant or minimized in the asphalt-emulsion/aggregate radon barrier system. However, there are four factors which may contribute to the degradation of asphalt in the radon barrier system--autoxidation, microbial attack, aqueous leaching, and temperature cycling. These factors are discussed below.

## Autoxidation

Autoxidation is the spontaneous reaction of a compound with molecular oxygen at room temperature. The limiting conditions imposed by the terms spontaneous and room temperature are artificial, since most autoxidations are accelerated by light or by traces of catalysts, or decelerated by antioxidants.

The autoxidation of organic compounds is considered a free radical reaction and has been exhaustively reviewed (Kochi 1973; March 1977). Important factors that determine autoxidation susceptibility are the free radical initiation rate and the efficiency of free radical chain propagation. Autoxidation is light-catalyzed and occurs much faster in solution than in the solid state. Typically, a carbon-hydrogen bond (C-H) reacts with atmospheric oxygen to form a hydroperoxide (C-O-O-H). The hydroperoxide can react further to produce alcohols, ketones, and more complex products. Ultraviolet light can transform ground-state oxygen into singlet oxygen. Singlet oxygen readily reacts with substituted alkenes to produce hydroperoxides. Atmospheric hydroxyl radicals can initiate reactions and photosensitized (triplet state) aromatics can react with ground-state oxygen from the atmosphere. Efficient chain propagation does not occur in the solid state because low molecular mobility favors free radical chain termination. Aldehydes, ketones, carboxylic acids, and dicarboxylic acids are typical autoxidation products, and autoxidation can increase aromaticity and molecular weight. In asphalt, crosslinking and polar, oxidation product, hydrogen-bonding produce high molecular weight asphaltenes. Most organic compounds autoxidize; foods, rubber, paint, and lubricating oils deteriorate with time upon atmospheric exposure.

Several factors affect the autoxidation rate of asphalt. Eliminating light and ambient free radical initiators (atmospheric species) should drastically slow the oxidation rate. In solid asphalt, free radical chain propagation is inefficient, and autoxidation is a gas/solid reaction. The inital oxidative weathering of asphalt causes an asphaltene skin to form on the surface. This protective asphaltene skin slows oxygen transport into the bulk asphalt, thus retarding the autoxidation rate (Van Oort 1956; Gotolski, Smith and Roberts 1968; Vind 1967). Wright and Campbell (1962) showed that the surface area of an asphalt film is more important than film weight in determining durability. Several studies indicated that the extent of oxidation of thin asphalt films was a hyperbolic function of time (Martin 1964; Van Oort 1956; Kleinschmidt and Snoke 1959; Lee 1973). These results indicate that the asphalt degradation rate in the radon seal, due to autoxidation, should slow after the first few years of service.

The unusual engineering aspects of the asphalt-emulsion/aggregate admix radon seal system limit the possibility of failure due to autoxidative asphalt fatigue. Normal asphalt road pavements have a very high internal surface area due to the voids content. Also, the asphalt in these pavements forms a thin film about the aggregate because of the low overall asphalt content. These two factors make asphalt pavement interior very susceptible to autoxidative degradation. The admix in the radon seal has a high asphalt content and low voids volume. As a result, the asphalt in the admix seal tends to be a continuous bulk phase and autoxidation should occur primarily at the admix surface. The formation of an outer asphaltene skin on the admix would limit oxygen diffusion to the seal interior, further inhibiting autoxidative asphalt failure. Asphaltene skin erosion should be prevented by the protective overburden. The overburden also protects the seal from sunlight and may reduce oxygen and hydroxyl radical exposure to the asphalt; this will limit the initiation of autoxidation reactions. Furthermore, the asphalt is not exposed to nitrogen oxide, and other internal engine combustion products that can cause autoxidation (Campbell and Wright 1965). The overburden reduces the mean exposure temperature for the admix in comparison to road pavements. Lower temperatures slow oxygen transport and thermal auto-oxidation reaction rates. The asphalt-emulsion/aggregate admix coupled with a protective overburden layer is a different physical system than asphalt road pavements; seal durability predictions based solely on road exerience are tenuous.

## Microbial Attack

The importance of slow, long-term microbial attack on the asphalt in the seal is unknown. ZoBell and Molecke (1978) have reviewed the microbial degradation of asphalt in relation to nuclear waste management. Asphalt degradation in road pavements and pipe coatings has been linked to slow, microbial action. Reclamation of soils contaminated with petroleum has been done by innoculating the soil with oil-digesting bacteria (Odu 1977a; 1977b). However, asphalt is less susceptible to microbial degradation than oil, probably because high molecular weight aromatic resins and asphaltenes are refractory to microbial attack (Vind 1967; Cundell and Trapler 1973). Interestingly, most antioxidant additives for asphalt stabilization are biocides (Vind 1967).

The rate of microbial attack depends on the amount of asphalt surface area exposed to oxygenated water (ZoBell and Molecke 1978). The low-surface-area/asphalt-weight ratio of the admix seal should slow the rate of microbial degradation. If the overburden slows oxygen transport to the admix, the microbial digestion may be inhibited due to a localized oxygen depletion. If microbial degradation of the admix seal does occur under Grand Junction field conditions, the rate is unknown and may be slow enough for the seal to last 1000 years. It is of interest to note that during the testing of canal liners under optimum growth conditions for bacteria, only about a 1-mil (0.025-mm) thickness of asphalt was affected in 3 years (Jones 1965).

Aqueous Leaching

The function of water in the natural weathering of asphalt is to leach oxidized constituents and so promote erosion, but not to contribute significantly to the age hardening (Martin 1964). Films of asphalt were immersed in water after exposure to ultraviolet light. When these samples are compared to controls, no significant difference could be determined in their relative viscosities. Thus, water immersion did not appear to influence the hardening of oxidized films. However, this does not mean that moisture is unimportant, since it has been shown that relative humidity during oxidation may influence the rate of leaching (Campbell et al. 1962). Furthermore, the performance of protective coatings or surfacing--such as gravel, mineral chips, and paint--is certainly influenced by rain, which would thus contribute to the long-term durability of asphaltic roofing materials. Later work has shown water-soluble components, produced by photo-oxidation, orginated from the lower molecular weight fraction of asphalt (Oliver and Gibson 1972). This work was rather definitive since it used tritium labeling experiments.

Temperature Cycling

The major experience with cycle temperature degradation of asphalt has been derived from the paving industry. The most important component of temperature cycling depends on low-temperature exposure. Freeze-thaw exposure of asphalt aggregate generally results in debonding of the asphalt from the aggregate due to water in the interstitial voids of the admix. This process, stripping, is probably responsible for more northern U.S. asphalt pavement deterioration than any other factor (Barth 1962). It is very difficult to measure the stripping phenomenon since the shape and size of aggregate particles contribute to a nonreproducibility of physical properties. This nonreproducibility of physical properties manifests itself as variations in asphalt properties such as permeable and nonpermeable void content and in the mechanical interlocking or packing of aggregate particles (Plancher et al. 1980). Variations in void permeability significantly affect the access of water to the asphalt-aggregate bond.

There are several related factors that can contribute to temperature-cycling degradation of asphalt besides freeze-thaw exposure. For instance, volatilization is the removal of the lighter oils from asphalt and is dependent upon time and temperature. Steric hardening (age hardening) is a phenomenon that occurs in asphalt at temperatures below the softening point of asphalt (Gotolski et al. 1968). Asphalt contracts with decreasing temperature. This contraction between asphalt molecules forms a tighter structure in the asphalt. This structure is somewhat thixotrophic in nature in that most of the structure is destroyed by the application of heat or mechanical energy (Barth 1962). Steric hardening is not a completely reversible process since some permanent hardening does occur.

Temperature-cycling degradation of asphalt can be related to the distribution and dispersion of its components. These components are sorted into broad solubility classes: maltenes are the pentane-soluble asphalt components, and asphaltenes are all of the pentane-insoluble components. The asphaltenes are high molecular weight polyaromatics and hydrogen-bonded aggregates of polar compounds (Boduszynski 1979; Speight and Moschopedis 1979). Maltenes contain relatively non-polar oils; paraffins, and aromatic resins (O'Donnell 1951). The resins occupy an intermediate oxidation level between the saturated oils/paraffins and the asphaltenes (Speight and Moschopedis 1979). The mean molecular weight distribution of asphalt fractions ranges from ~4000 amu for asphaltene polyaromatic sheets to ~600 amu for saturated maltenes (Kiet, Blanchard and Malhotra 1977). Asphalts do not have a uniform composition; the asphaltene to maltene ratio varies with the asphalt source as does the weather resistance (Heithaus 1962). The viscosity, softening point, and other physical properties of asphalt are largely determined by the extent of the asphaltene phase (Altgelt and Harle 1975; Corbett and Petrossi 1978; Vind 1967). The lower molecular weight maltenes have been characterized as asphalt plasticizers. Natural asphalts have a higher asphaltene content than modern semi-synthetic asphalts (Vind 1967). The durability of asphalt correlates with the homogeneous dispersion of the asphaltene phase throughout the asphalt (Plancher et al. 1979).

## PRELIMINARY EXPERIMENTAL RESULTS

Several preliminary leaching experiments were performed on different types of asphalt seals, and methods of chemically characterizing the asphalt were tested. These results have allowed us to gain insight into the design of experiments for the determination of the long-term asphalt-emulsion admix seal stability. The combined results of our literature search and experimental work indicate that asphalt autoxidation, aqueous leaching, and microbial attack are the most likely mechanisms for asphalt degradation (Oliver and Gibson 1972; Van Oort 1956; Vind 1967; ZoBell and Molecke 1978). The literature search also indicated that cracking due to temperature cycling (freeze-thaw stress) and subgrade settling might be a generic problem to all the proposed seal technologies. An experimental plan for FY-81 studies is presented in Appendix B.

Several leaching experiments were performed to determine the importance of certain factors that affect asphalt stability. Fog seals prepared from different asphalt emulsions were chemically analyzed using elemental analysis, gel permeation chromotography (GPC), proton and carbon 13 nuclear magnetic resonance (H'-NMR & $C^{13}$-NMR), and infra-red (IR) spectroscopy. The oxidation susceptibility of asphalt in solution was also tested. The results of these experiments are discussed below.

### Leaching Experiments

Preliminary leach tests were carried out on an admix seal prepared with Grand Junction tailings and Armak 4868 asphalt emulsion. The test specimens were leached at room temperature for 5 days in a variety of acid solutions at a pH of 2 in order to simulate the worst case at the Grand Junction tailings pile. The acids used were $HNO_3$, HCl, $H_2SO_4$ and aqua regia. Weight loss in all cases was less than 0.4 wt% which is attributed to the leaching of exposed tailings on the surface. No asphalt deterioration was observed. The major elements detected in the leach solutions were Ca, Mg, Al, K, Na, Fe, and V. In addition, three experiments were undertaken to explore the effect of aqueous leaching on asphalt emulsion systems. In the first experiment, the stripping susceptibility of asphalt emulsion fog seals was investigated under simulated field conditions. Five leaching cells (see Figure 10) were constructed using 6-in. Lexan® piping, polyethylene tubing, Teflon® tubing, latex gaskets, polypropylene fittings, and a peristaltic pump. Brine was pumped from the reservoir, dripped onto the fog seal, and returned to the reservoir. The 6.4-mm- (1/4-in.-) thick fog seals were prepared by gently pouring emulsion over a 7.6-cm- (3-in.-) thick quartz sand layer. The seals were cured by storing the open leach cell in a high air flow hood for approximately 21 days. The brine was prepared to simulate tailings ground water (Gee et al. 1980). Thus, to 600 ml of distilled water we added 0.57 g $Na_2SO_4$, 0.22 g $NaNO_3$,

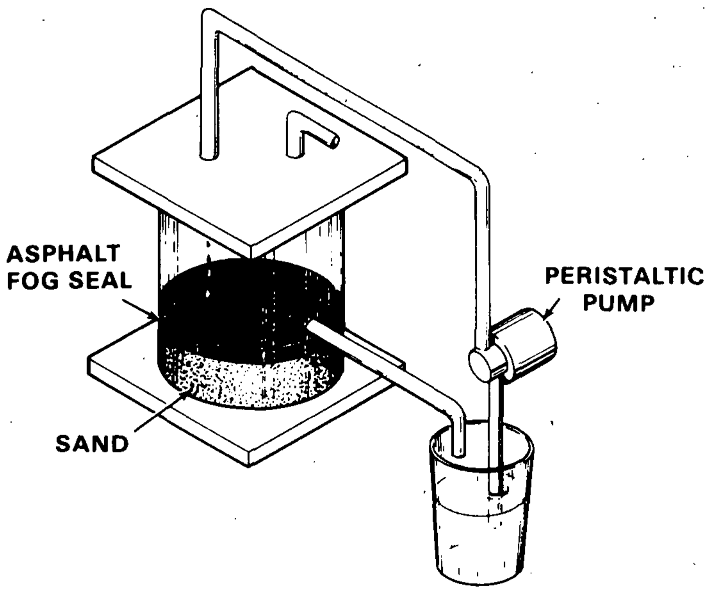



FIGURE 10. Apparatus for Aqueous Leaching of Selected Asphalt Emulsion Fog Seals

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®Teflon is a registered trademark of duPont, Wilmington, Delaware.

0.15 g NaCl, 3.20 g $MgSO_4$, and 1.21 g $CaCO_3$. Sufficient concentrated sulfuric acid was added to dissolve the $CaCO_3$. To this solution were then added 7.13 g $Al_2(SO_4)_3 \cdot 18\ H_2O$ and 11.00 g $FeSO_4 \cdot 7\ H_2O$. The solution volume was brought to 1 L while the pH was adjusted to 2.

Five different asphalt emulsions were individually tested as fog seals (see Table 10). Four days of leaching caused three of the five seals to fail, because of asphalt dissolution into the brine. Two of the five seals showed no dissolution tendencies and remained intact. It was concluded that the three fog seal failures were due to insufficient curing, indicating that proper curing is an important factor in determining asphalt resistance to stripping.

In the second experiment, a slightly different experimental design was used to test the inadequate curing assumption. The cationic emulsion that gave the worst performance in the first experiment (emulsion 5) was selected for seal preparation. The fog seals were made by pouring 40 ml of emulsion into each of five 250-ml Erlenmeyer flasks. Air was blown over the seals for 3 days. The flasks were then stored in a vacuum drying oven for 2 days at $100^{o}C$. The flasks were placed in a $100^{o}C$ drying oven for 2 additional days. Approximately 100 ml of the simulated ground water was poured into each cooled flask, and the stoppered flasks were mechanically shaken for 15 days.

TABLE 10. Asphalt Emulsion Tested During Aqueous Leaching Studies

| Sample No. | Source | Treatment | Description | Stripping Results |
|---|---|---|---|---|
| 1 | Edgington, CA | untreated | 26 mV, pH 2.8<br>60% solids | not stripped |
| 2 | Lyon, AK<br>(Smackover Crude) | proprietary treatment | 18 mV, pH 1.3<br>60% solids | moderately stripped |
| 3 | Lyon, AK | untreated | 21 mV, pH 1.07<br>60% solids | not stripped |
| 4 | Oklahoma City, OK | proprietary treatment | 18 mV, pH 1.07<br>60% solids | badly stripped |
| 5 | Oklahoma City, OK | untreated | 20 mV, pH 0.97<br>59% solids | excessively stripped |

After 5 days of vigorous agitation, the liquid began to change from clear to murky dark brown while the previously smooth seal surface began to pucker. Filtration through a medium porosity, sintered glass funnel removed the suspended asphalt solids and produced a clear, slightly yellow filtrate. The residual asphalt seal was also much softer after the leaching. The pH of the brine did not change over the course of the experiment. Some water uptake into the seal probably occurred, which caused the asphalt to soften. Since the asphalt did not appear to dissolve, the observed stripping may have been due to the abrasive action of the brine on the seals during agitation. This experiment indicated that both the level of curing, water flow conditions, and emulsifier action are important factors affecting asphalt stability.

In the third experiment the stabilizing effect of the aggregate was examined since asphalt emulsions are designed for use as an admix. Two 1-1/2-in.-thick asphalt-emulsion admix seals were prepared from +56 mV Armak cationic emulsion and Hanford blowsand. They were then drip leached with simulated tailings ground water as in the first experiment. After 60 days, no identifiable change had occurred. The experiment is continuing.

The higher resistance of untreated Oklahoma City asphalt in the second experiment to stripping under more severe conditions illustrates the importance of proper curing on stability. Although the emulsifier causes the asphalt to absorb water, the combination of benign flow conditions and asphalt aggregate bonding stabilized the system as shown in the third experiment. These three experiments indicate that simple variations in the asphalt system can produce different outcomes in stability experiments. Our preliminary results underscore the importance of exactly duplicating the admix-overburden seal system in future stability determinations.

## Elemental Analysis

The carbon, hydrogen and nitrogen analyses for seven asphalt emulsions were obtained. The average ($\pm$ standard deviation) of these analyses indicated that the asphalts as a group were highly aliphatic. These values are:

| | |
|---|---|
| Nitrogen (by wt%) | 0.4% $\pm$ 0.3% |
| Carbon (by wt%) | 86.2% $\pm$ 3.2% |
| Hydrogen (by wt%) | 11.2% $\pm$ 0.7% |
| Hydrogen: carbon mole ratio | 1.6% $\pm$ 0.1% |

This highly saturated structure is also confirmed by IR and NMR.

### Gel Permeation Chromatography

Gel permeation chromatography (GPC) is a standard method of determining the molecular weight distribution of a sample. The calibration curve utilized linear polystyrene of known molecular weight. Since asphalt may have a different molecular shape than the polystyrene standard used for a calibration curve, the chromatograms provide only qualitative information. All samples showed a bimodal molecular weight distribution. Typical chromatagrams are shown in Figure 11 (samples labeled A). The maxima at 11.73 in Figure 11 (sample 3A) represents the asphaltene 2500 amu fraction and the maxima at 13.5 represents the maltene 700 amu fraction. Changes in the molecular weight distribution are particularly easy to detect using GPC.

Since the GPC chromatograms provided a fair amount of molecular weight separation, an experiment was performed to determine the oxidation susceptibility of asphalt in dilute tetrahydrofuran (THF) solution. THF solutions of three asphalts were prepared and GPC analysis was performed. After 60 h of storage with air exposure, a further GPC analysis was performed. Comparison of the before (A) and after (B) GPC chromotagrams shown in Figure 11 illustrates a dramatic increase in the asphaltene peak at the expense of the lower molecular weight components. This experiment helped develop our analytical capability for detecting oxidation-induced changes in the chemical composition of asphalt.

### Nuclear Magnetic Resonance Spectroscopy

Proton (H') and $C^{13}$-NMR are useful tools in determining the relative distribution of compound classes in asphalt. Chemical changes in asphalt caused by oxidative weathering might be detected with NMR. Spectra of eight samples were obtained and found to be quite similar. The proton NMR showed that the asphalts were predominantly aliphatic with approximately 30% aromaticity. A

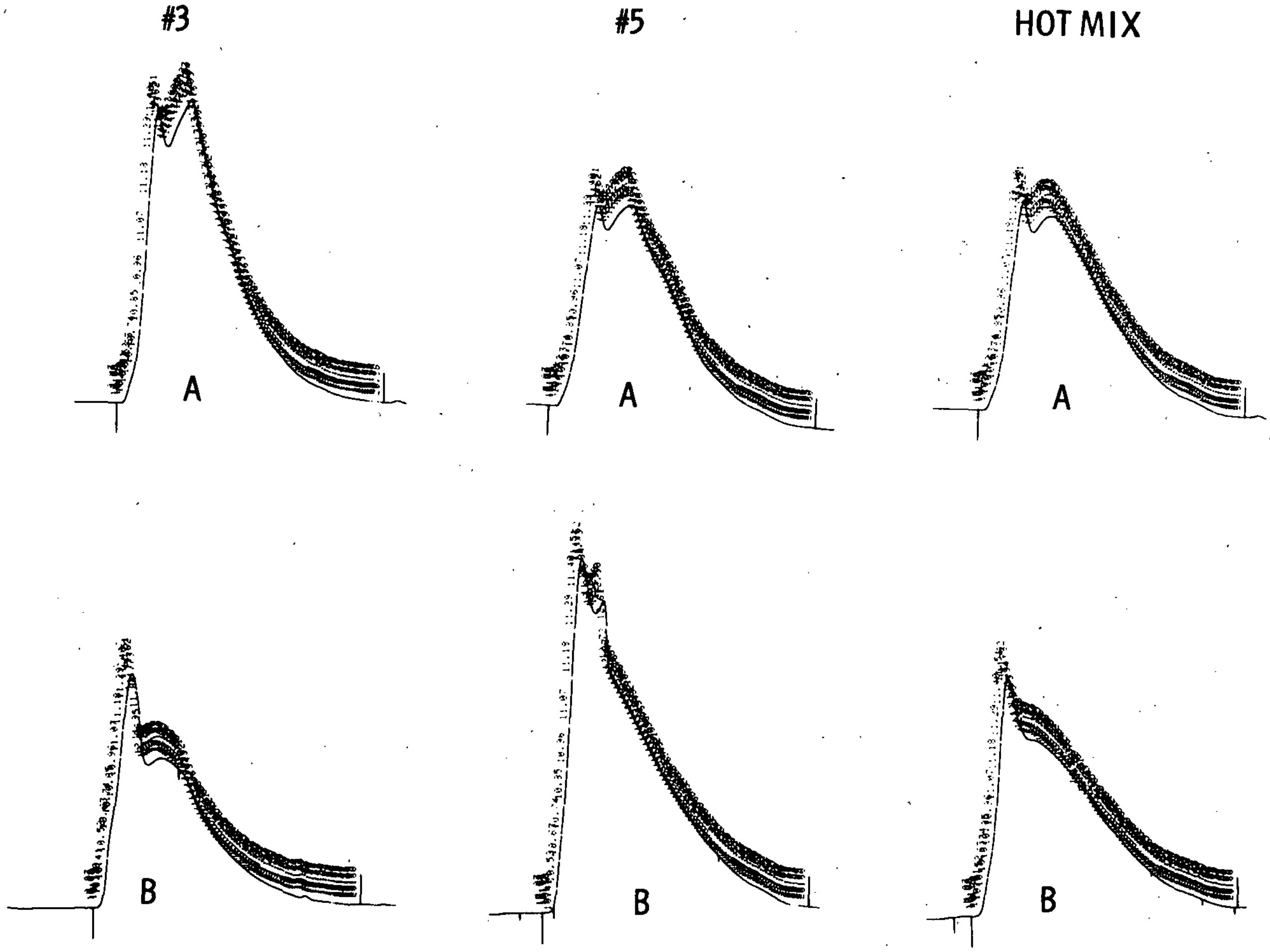


FIGURE 11. GPC Chromatograms of Asphalt Emulsions Before (A) and After (B) Air Oxidation

typical proton NMR spectrum (Armak +54 mV emulsion) is shown in Figure 12. Quantitative $C^{13}$-NMR showed Armak +54 mV emulsion had about 30% aromaticity (see Figure 13). This emulsion had essentially no olefin fraction. Changes can be detected at about 5 wt% by NMR.

## Infra Red Spectroscopy

Infra red (IR) spectroscopy is complementary to NMR while providing information concerning the oxygen content. Five IR spectra were obtained. These spectra were all very similar and supported the NMR conclusions that the asphalt emulsions were highly aliphatic with low aromaticity. The asphalt

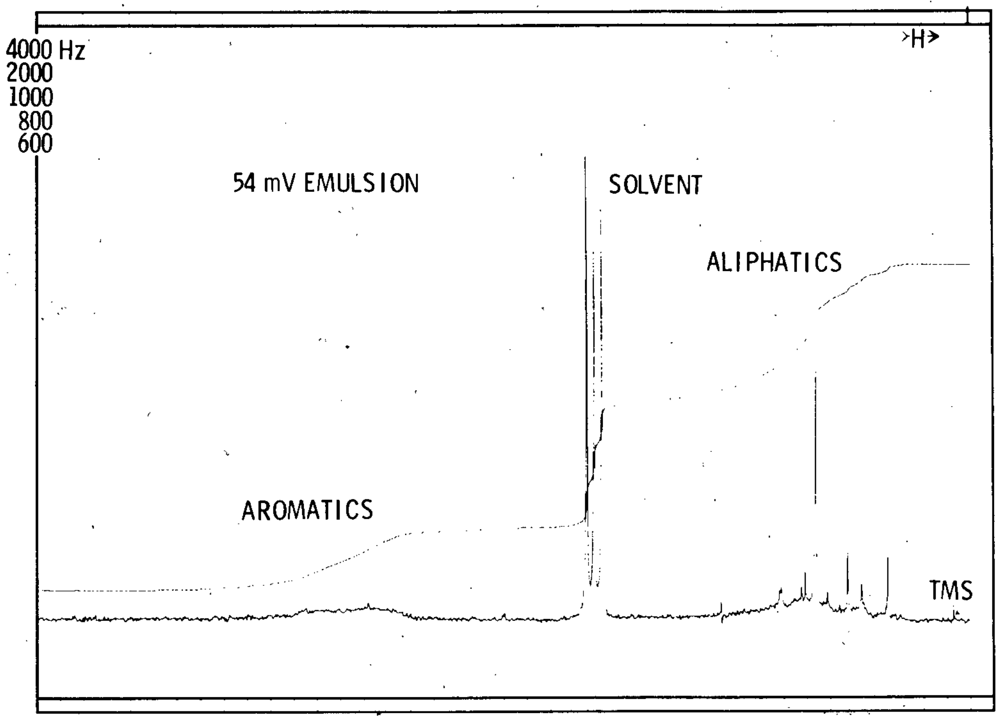


FIGURE 12. Proton NMR of Armak +54 mV Emulsion

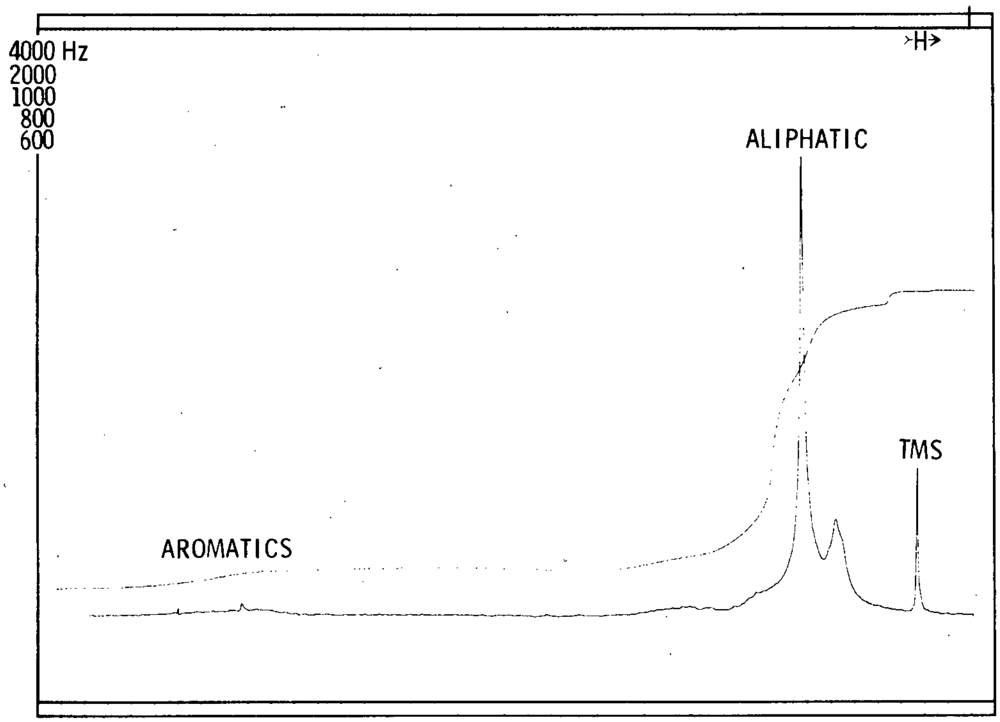


FIGURE 13. $C^{13}$-NMR of Armak +54 mV Emulsion

emulsions contained no carbonyl (C=O) functionality. All spectra were obtained from samples that had been dissolved in carbon tetrachloride. A typical IR spectrum is shown in Figure 14.

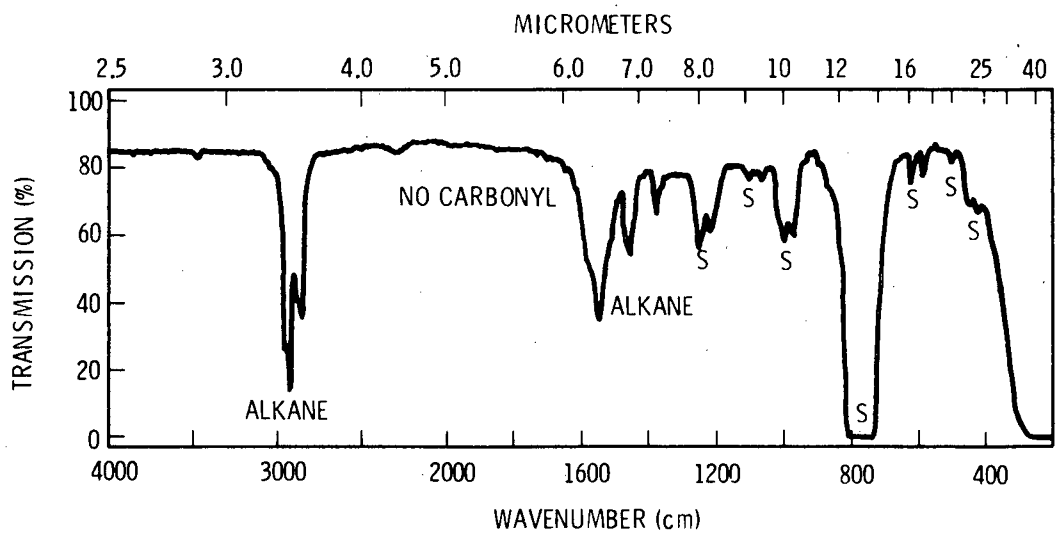


FIGURE 14. Infrared Spectrogram of a Typical Asphalt Emulsion Sample

## FIELD STUDIES

Field studies were conducted to determine the effectiveness of the PNL-developed radon barrier system. Activities carried out during FY80 included 1) evaluation of application equipment and technologies, 2) the field test at Grand Junction, Colorado, and 3) development of an improved radon flux field measurement system.

The evaluation of application equipment and technologies consisted of a review of current asphalt application techniques and identification of techniques that could be used or modified to apply a reliable and cost-effective radon seal. This was accomplished by:

- conducting a literature search on asphalt and asphalt-emulsion application techniques and identifying those techniques that can be used with a high asphalt content
- obtaining input from experienced people in the asphalt industry
- conducting small-scale field screening tests on selected techniques
- reviewing PNL laboratory and field test results.

In addition, criteria were established for selecting application equipment based on the ability of a technique to apply a mechanically stable and radon-tight seal. The equipment must be able to mix and apply an admixture consisting of a fine aggregate (such as concrete sand) and 30 to 40 wt% asphalt emulsion (18 to 24 wt% residual asphalt). The equipment must be able to apply the mix while operating on a 20% slope. The technique should require only minimal base preparation, and the equipment should be commercially available with minimal modifications.

From the research results, the following equipment was selected for further review.

- cold-mix paver
- pugmill
- soil stabilizer
- transit mixer

- chipsealer
- pneumatic gun
- drum dryer
- batch plant
- fog seal.

The objective of the field test was to evaluate the effectiveness of an asphalt emulsion radon barrier system using application techniques identified in the application technology studies. The construction of the radon barrier system not only allows the evaluation of the technical feasibility of seal application on a realistic scale, but it provides an opportunity to evaluate:

- application techniques and procedures
- site preparation requirements
- radon flux reduction and diffusion
- characteristics of final seal and radon barrier system
- reclamation requirements including biobarrier and revegetation.

To evaluate the effectiveness of the various sealing procedures, a method was required for measuring the radon flux before and after seal application. The radon flux measurement system used in the 1979 field studies was somewhat inconvenient; thus an improved system was designed, constructed and used in the 1980 field studies.

## EVALUATION OF APPLICATION EQUIPMENT AND TECHNOLOGIES

This section describes the application equipment, identified during the initial equipment review, that had a technical possibility of successfully applying a radon seal. Selected equipment were screened in small-scale field tests. These field tests were typically conducted with less than 20 t of material, and 7600 L (2000 gal) of asphalt emulsion. The tests were used to evaluate the asphalt-emulsion/aggregate mixing characteristics of the machinery and the characteristics of the final product. Cost data were also obtained where appropriate.

## Cold-mix Paver

The first promising piece of equipment identified during the initial equipment review was the cold-mix paver. This paver meters a calibrated flow of asphalt emulsion and aggregate into a pugmill producing a well-mixed admixture that is then paved in a continuous operation. From the results of a small-scale equipment screening test, the cold-mix paver appeared viable for field testing if some minor modifications to the screed and aggregate feed system were made.

The cold-mix paver is designed as a combination aggregate/asphalt emulsion mixer (pugmill) and aggregate/asphalt emulsion admixture laydown machine. Currently, its primary commercial use is to make open-graded road pavements (i.e., pavements designed with a broad size range aggregate, but with few fines).

The cold-mix paver operation is shown in Figure 15 and graphically illustrated in Figure 16. Aggregate is fed initially into the hopper in the front of the cold-mix paver. A calibrated volume of aggregate is continually carried by a conveyor to a mixing chamber consisting of a horizontal twin-shaft pugmill, recognized by the industry for its superior mixing capabilities. Asphalt emulsion is metered in the front end of the pugmill where it is thoroughly

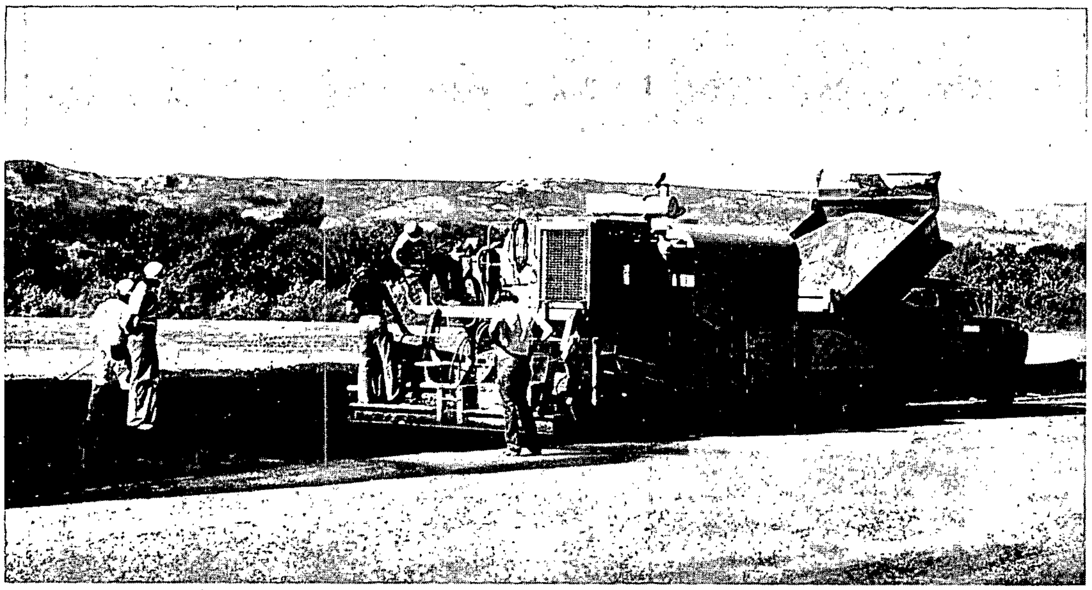

FIGURE 15. Cold-mix Paver in Operation

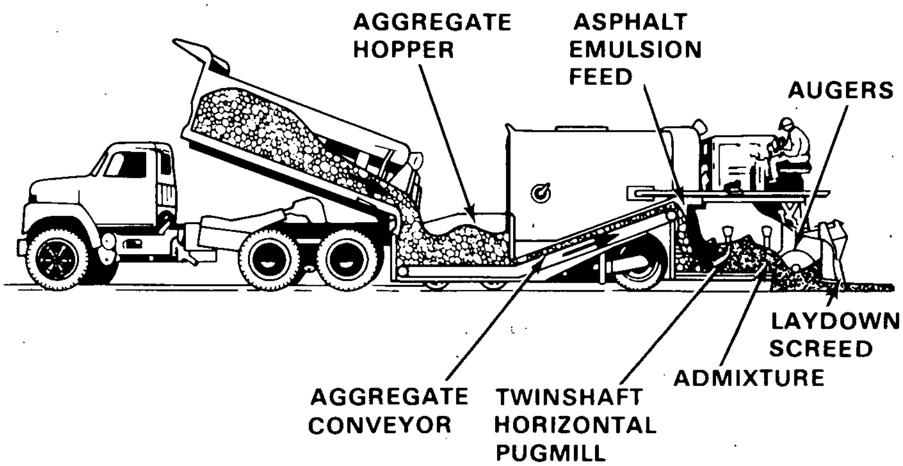


FIGURE 16. Cold-mix Paver

mixed with the aggregate by the pugmill paddles. The admixture product exits out the back of the machine where augers spread it the width of the laydown screed (Figure 17). The height of this hydraulically controlled screed determines the depth of the admix seal.

FIGURE 17. Cold-mix Paver Laydown Screed

The cold-mix paver has several advantages:

- is designed for use with asphalt emulsions
- provides onsite mixing and laying and thus avoids admixture handling problems
- has a short mixing time allowing the use of faster-setting emulsions, thus lowering the potential for emulsion runoff
- allows semicontinuous operation
- provides a potential production rate of 1500 t/day
- has an easily and instantaneously adjustable screed permitting more accurate control over seal depth
- appears easily modified to obtain the high asphalt concentrations.

The disadvantages of the cold-mix paver include: 1) the high total weight of the operating machine (40 t), indicating the need for careful site stabilization, 2) the extent of control over the aggregate feed rate and the asphalt pumping rate, and 3) the uncertainties of using the stock admixture spreading unit (screed).

A cold-mix paver screening test was conducted in Colfax, California, to 1) observe the operation of the paver on poorly prepared dirt roads, 2) gather data on variability in mix, and 3) determine the suitability of the stock screed for high-asphalt-content admixes.

Several admixture strips, approximately 3 m x 18 m, were laid adjacent to each other. The admixture, composed of concrete sand and Union 76 CMS cationic asphalt emulsion, had several desirable qualities. The admixture, averaging ~19 wt% residual asphalt content, was an 8-cm deep mastic mass that formed joints easily and did not slump excessively after being laid.

The California screening test proved the cold-mix paver can be used to mix concrete sand with Union 76 asphalt emulsion, forming an admix with ~19 wt% residual asphalt. The coating of the aggregate in the cold-mix paver was acceptable. The control over the mix was respectable enough, but could be improved. However, the results of the tests indicated that some modifications were needed to use the cold-mix paver for the radon seal application at the Grand Junction tailings site.

- Substantial base preparation is required to support the front wheels on the cold-mix paver.
- Calibration and precision of the asphalt emulsion pump and aggregate feed mechanism have to be improved.
- The admixture spreading mechanism needs to be modified or replaced with one suitable for radon seal application.
- The capacity of the asphalt emulsion pump should be doubled.
- A continuous feed system to the aggregate surge bin is needed.

Discussions with the manufacturer revealed pressure exerted by the tires could exceed 70 psi with the cold-mix paver. For propelling such a heavy machine, caterpillar tracks would have been preferred over high float tires in off-road situations. These discussions, along with the results of the screening tests in California, indicated special design criteria must be established for the tailings stabilization before the cold-mix paver can be used.

The extent of control available over the final mix was another concern. Aggregate feed to the pug is determined by gate height and belt speed, lending itself to variability in feed rate by density changes in feed, and variability of belt speed under load.

Related to this, as both are driven by the same interconnected hydraulics, is the calibration and accuracy of the asphalt pump. When the other systems are under load, the pumping accuracy is affected to an indeterminate extent, especially at the high pumping rates required. Monitoring of the variability in the final mix should determine the seriousness of this problem.

The final major concern was over the suitability of the stock screed for spreading the mix after it came from the pugmill. With the stiff road mixes for which the cold-mix paver is designed, the screed is supported on the road mix surface. Pavement depth is determined by the angle at which the screed is held in relation to the pavement mixture. Such a system did not work with the high-asphalt-content mixture. Consequently, skids, tack-welded to the base of the screed, had to be used to support and adjust screed height. The hydraulic screed adjusting system could independently support the screed but would have to be continually monitored.

Doubling the capacity of the asphalt emulsion pump and obtaining a continuous aggregate feed system would improve the production rate of the cold-mix paver for the high-asphalt-emulsion contents.

Continous Portable Pugmill

One piece of equipment thought to be well suited for mixing asphalt emulsion admixtures for radon seals over uranium mill tailings piles was the continuous portable pugmill. This equipment continually meters a calibrated flow of asphalt emulsion and aggregate into a pugmill producing a well-mixed product that can be rapidly transported to the paving site.

In the asphalt paving industry, the portable pugmill is used mainly for construction and maintenance of rural road surfaces. It is equipped for travel so that product transportation from the pugmill to the paving site is minimized. The pugmill, shown in Figure 18, consists of an aggregate hopper, a material transfer belt, and the pugmill from which the asphalt/aggregate admixture falls into the dump truck for transfer to the paver.

A typical pugmill is depicted graphically in Figure 19. Aggregate flow is controlled by a manually adjusted gate located at the bottom of the hopper. A periodically operated vibrator keeps the aggregate from bridging for a uniform flow. The material flow over the belt is monitored by a load cell that automatically proportions the emulsion pump for the desired residual asphalt concentration in the cured admixture. The aggregate strikes a deflector plate at the top of the pugmill, directing the point of entry which helps control the time of mixing. Water can be sprayed onto the aggregate via a water pump and spray bar just before the aggregate enters the pug. The asphalt emulsion is introduced at the back end of the 150-cm pugmill, which mixes the material with 48 paddles connected to two parallel shafts. The paddles are reversible for better mixing control.

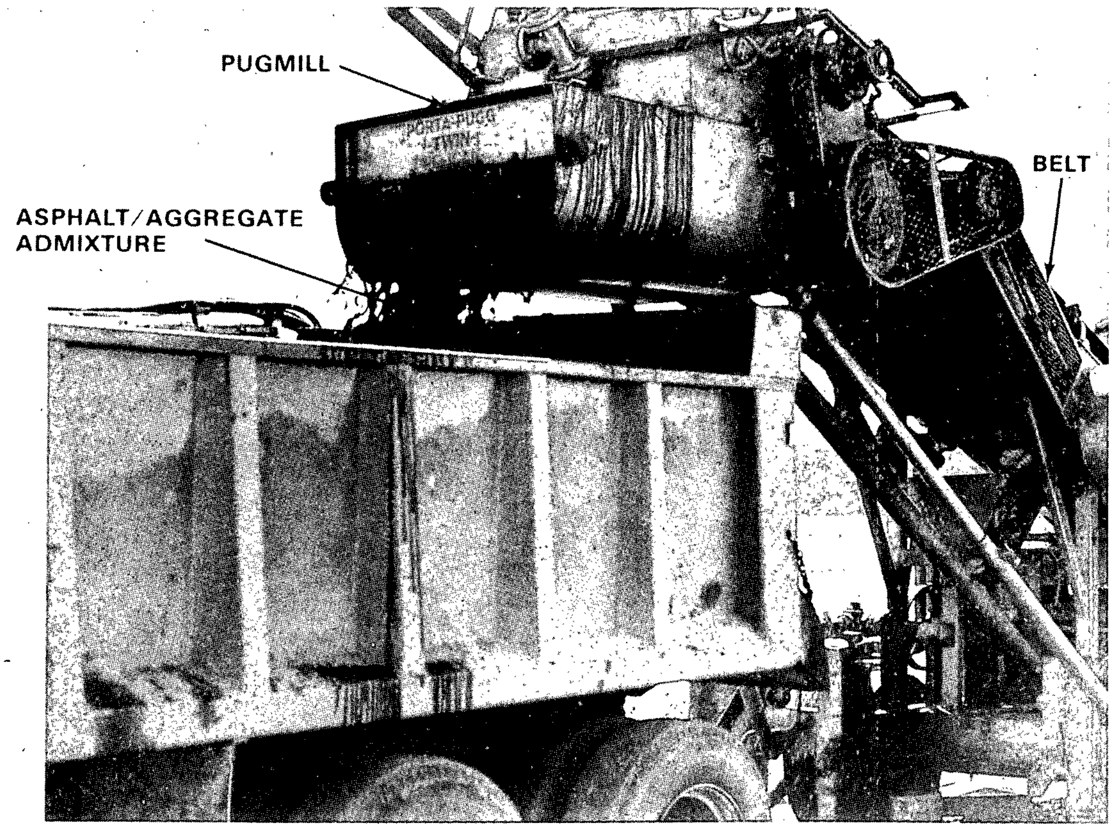


FIGURE 18. Continuous Portable Pugmill in Operation

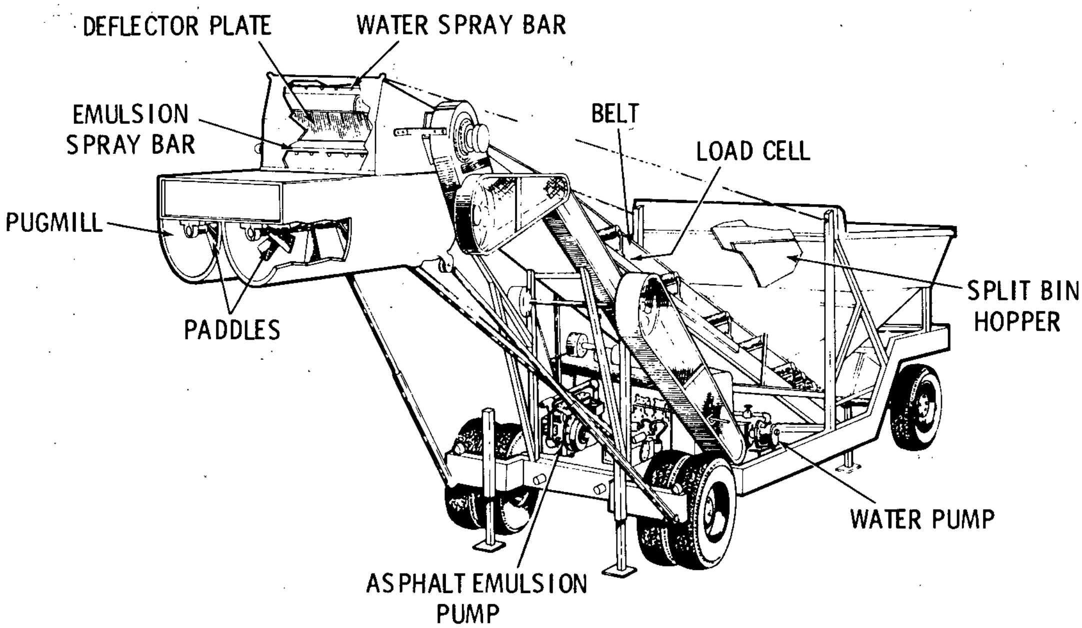


FIGURE 19. Continuous Portable Pugmill

Initial evaluations showed the continuous portable pugmill to be extremely attractive for mixing radon seal materials. The pugmill offers one of the best aggregate coating of central plant mixes and still maintains job-site control of the product quality (Caldwell 1975). Since the pugmill is located at the job site, the admixture can be rapidly transported to the paving site while it is still workable for paving operations. Also, pugmills are excellent for controlling mixing times of CMS emulsions between 5 and 15 s (Pollock 1975). The major potential disadvantage of the system is that the resulting admixture must be transported to a paver.

Use of the pugmill for seal application involves the following steps: 1) mixing and transferring the asphalt emulsion and admixture into trucks, 2) hauling the admixture to a standard asphalt laydown machine, and 3) working the admixture through the asphalt laydown machine to form an 8-cm-thick cover.

A preliminary screening test in Oregon was conducted with a portable continuous pugmill to determine the advisability of subsequent field tests for forming an admixture with 25 wt% residual asphalt. Numerous calibrations and adjustments of the asphalt pump and aggregate belt were performed to obtain the high residual asphalt content desired. Due to the pugmill's inadequate pump capacity, the calibrated asphalt content was only 18.6 wt%, shy of the 22 to 25 wt% desired range. A total of 6.9 t of concrete sand and 2080 L (540 gal) of CMS emulsion were then mixed and laid in a 3-m x 27-m strip.

The coating of the aggregate in the test strip was excellent, demonstrating the pugmill's good mixing characteristics. Some uncertainties remained, however, because of the 6.5 wt% hydrocarbon solvent in the emulsion used in this test and the deficiency of asphalt in the paved test strip. Seal formulation studies for this cover technology program identified a CMS asphalt emulsion for radon seals containing no hydrocarbon solvent. Even though solvents acts as lubricants keeping materials workable for longer periods of time, they are not considered for cover technology because of the possibility of outlawing the use of petroleum diluents in road paving materials (Hatfield 1978). The material evaluated in the screen test was workable long enough to be paved, but the uncertainty exists in whether the same results would be observed with solventless emulsions. The other uncertainty was that the measured asphalt concentration in the admixture was only 13.5 wt%. The discrepancy from the calibrated value is probably due to asphalt runoff when the water separated from the rest of the asphalt in the transfer truck. Through proper precautions, the pugmill can be set up to supply the proper amount of asphalt in the admixture, but the question arises as to how this will affect the workability.

Even with these uncertainties, the pugmill was attractive enough to be included as major test equipment for the Grand Junction field test. The screen test identified some precautions when applying a portable pugmill to cover technology.

- Measures must be undertaken to insure the high emulsion content in the admixture. This can easily be achieved by larger emulsion pumps and by sealing the transport trucks.
- Pugmill calibration is affected by numerous factors. Enough time during the field test must be set aside for calibration and frequent checks.
- Automated pugmills are preferred for ease of control and calibration.
- If a tracked asphalt laydown machine is used, minimal base compaction would be required.
- Asphalt emulsion should recirculate in the pipelines, never allowing the emulsion to be left stagnant in a transfer line.

<u>Soil Stabilizer</u>

A hydrostatic drive soil stabilizer (see Figure 20) was identified and used in the FY79 field test as an asphalt emulsion seal application technique (Hartley et al. 1980). The FY79 field test demonstrated the advantages and disadvantages of this technique. The soil stabilizer mixes asphalt emulsion and aggregate in situ, eliminating aggregate hauling costs. It can apply asphalt at a variety of application rates from a few percent residual asphalt to ~25 wt% residual asphalt with no modifications of equipment.

On the other hand, the soil stabilizer inconsistently mixes the tailings and emulsion, and it gives poor depth control, partially caused by a poorly compacted base.

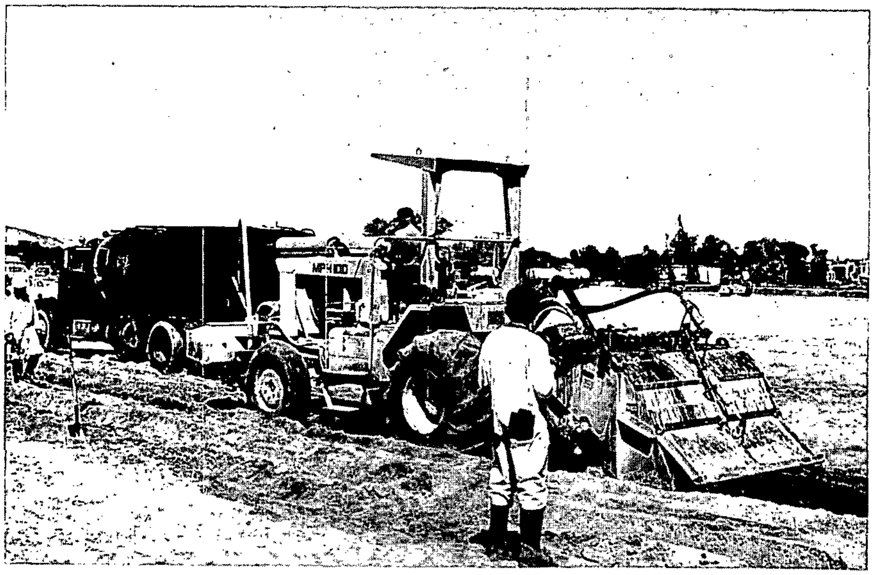

FIGURE 20. Hydrostatic Soil Stabilizer

Based on FY79 results (Hartley et al. 1980) we concluded that the soil stabilizer would be a suitable technique to try again in FY80. It was used in two different ways. The first was to apply ~5 wt% asphalt to the entire test plot providing a stable base on which other equipment could operate. The second was to apply ~22 wt% asphalt directly into the tailings to obtain a radon-tight seal. The mixing and depth control problems could be remedied by proper base compaction and water addition.

Transit Mixer

Use of a transit mix truck capable of mixing and transporting concrete was considered to mix high concentrations of asphalt emulsion and concrete sand. The mixture would be dumped from the transit mixer into a paver for seal application. The transit mixer shown in Figure 21 consists of a truck with a large drum and drum-drive system mounted on the rear. The drum has vanes mounted on the inside which can transport the mixed material to the bottom or top of the drum depending on the direction of drum rotation. The drum is capable of turning during transit or while stationary.


FIGURE 21. Transit Mixer

The transit mixer offers some important advantages. The mixing time can be controlled, it provides a portable mix plant that can be driven to any site, it is readily available in most locations, and it can continually mix asphalt and sand while transporting to a paver.

The disadvantages of the transit mixer are that it has a low capacity, i.e., 5 to 8 $m^3$ (6 to 10 $yd^3$), and it is not designed to handle asphalt emulsion. Furthermore, removing material from the drum may be a potential problem as asphalt mix can build up on the sides of the drum.

A modern transit mix truck capable of mixing and transporting 6.4 $m^3$ (8 $yd^3$) of concrete was tested in Eugene, Oregon. The tests were designed to determine if a transit mixer could mix and feed an asphalt-concrete sand mixture containing 22 wt% residual asphalt.

An initial test was run to determine if the transit mixer could feed a paver at a rate suitable for production purposes. The transit mixer was loaded with 4.8 $m^3$ (6 $yd^3$) of concrete sand and enough water to produce a mixture consistency similar to the asphalt-emulsion/concrete sand mixture obtained in the lab. The drum was then emptied as quickly as possible. This took 108 s, a rate shown to be suitable for production use.

The second test was to determine if the transit mixer could be used to obtain a well-mixed asphalt-emulsion/concrete sand mixture. The truck was loaded with 6.4 $yd^3$ of concrete sand, and 636 gal of CMS-2 asphalt emulsion was pumped into the drum with a transfer pump. The drum was slowly rotated at all times during the emulsion transfer, which took approximately 1 h. The resultant admixture was very stiff, resulting in difficulties in feeding the mixture to a paver. The mixture stuck to the sides of the drum and would not transport out of the drum at a sufficient rate. Water was then added to the mixture in an attempt to thin it. This was unsuccessful. Later analysis revealed that perhaps more CMS-2 emulsion should have been used as a diluent.

The test was abandoned and the trucks were cleaned with diesel fuel which eventually removed the gooey mixture. Constructive information was not obtained in this test other than the fact that short off-loading times can be achieved under ideal conditions. A further test was warranted using CMS emulsion without the addition of hydrocarbon solvents.

Slurry Sealer

The slurry seal truck also appeared to be a promising piece of equipment for the FY80 field test. However, the equipment screening test proved that too many modifications would be required to make it suitable for our purposes.

The slurry seal is essentially a thin coat of asphalt and aggregate commercially spread on parking lots or roads for a wearing or repair coat. The thin coat, usually the thickness of the largest aggregate present in the mix, contains an average 18 wt% asphalt emulsion. Some of the initial lab tests had admixture products similar in consistency to slurry seals, promoting interest in machinery such as the slurry seal truck, capable of handling such a fluid mix. The slurry seal machine consists of an aggregate storage bin, water and emulsion storage tanks, a mixer section, and a spreader section (Benedict 1977). The aggregate is fed to the mixer (pugmill) by a conveyor belt through a calibrated feeder gate which controls the flow. Water and asphalt emulsion are fed into the mixture by metering pumps. The slurry materials are mixed by a spiral or rotary type agitator and the slurry then spills from the mixer into the spreader box. Figure 22 shows a typical slurry sealer applying an asphalt emulsion seal.

FIGURE 22. Slurry Seal Machine

The merits of a slurry seal application system included:

- the design for higher asphalt contents
- inexpensive and uncomplicated operation
- provision for onsite asphalt mixing and laying
- minimal base preparation.

The disadvantages of the slurry seal system were:

- low production output rate, because of its batch operation
- difficulty in controlling depth with the slurry sealer
- inadequate mixing provided by the slurry seal pugmill.

After discussions with manufacturers, an equipment screening test was set up with a slurry seal truck in California. The brand of truck selected was generally agreed upon by competing manufacturers as having the best pugmill for mixing and coating in the slurry seal industry.

This California test proved a slurry seal truck can lay down a 5-cm uncompacted admix lift that can initially seal radon at 22.2 residual wt% asphalt, but only with the addition of aluminum sulfate to make a thixotropic mix (i.e., one with little runoff and that will maintain its initial height). In addition, other problems indicated that modifying the slurry seal trucks to make them suitable for the Grand Junction field test would not be practical.

First, control of the asphalt-emulsion/aggregate mixture ratios is completely dependent on the operator. Only by experience does he determine these ratios. In most cases, there are no aggregate weights or asphalt emulsion gallonages with which to calibrate and maintain the mix quality. Second, the admixture would be difficult to apply at 5- to 7.5-cm depths. The attained depth of mix was only possible with the use of an aluminum sulfate additive. This additive, added in rather large amounts, almost completely stopped runoff and with its thixotropic impact, insured the mixture would keep its 5-cm depth without rapid slump. It is very difficult to assess the impact of the additive on the long-term stability of a seal. Third, slurry seal trucks are just not designed for high production rates, especially at the high asphalt content. Overall capacity of the pug is limited by the size of the aggregate feed system to the pug and would require extensive modifications to obtain suitable production rates. Fourth, the single-shaft pug does not provide adequate mixing to insure good aggregate coating at even the low production rates that were tried. These problems, and others common to all the application systems, ruled out the slurry seal truck as a means of applying a radon seal.

## Drum Dryer

The drum dryer method of mixing asphalt and aggregate together was also considered in our initial equipment review (see Figure 23). This review determined the drum dryer unsuitable for our purposes. In the drum dryer, aggregate is fed into one end of the drum and asphalt is added in mix stages. The dryer is rotated and the admixture falls into a collection bin. The reason this process is not suitable is discussed below.

In spite of its reputation as a high production and tightly controlled operation, discussions with manufacturers' representatives revealed reasons to

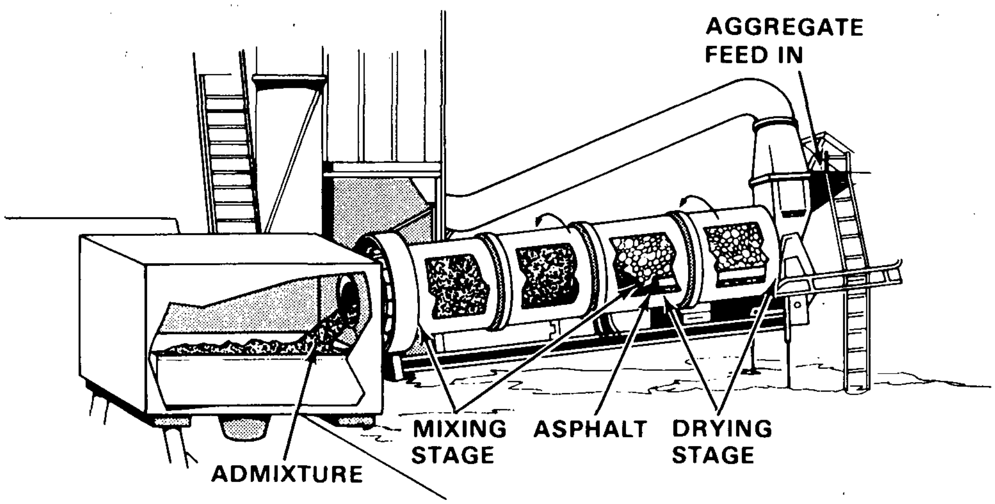


FIGURE 23. Drum Dryer

disregard this process. In their opinion, problems could be expected from the high fine content present in our aggregate, such as concrete sand or tailings. In addition, it would be expensive to set up a plant onsite at a tailings pile. Finally, problems would be encountered in handling an admixture from plant to paver.

To expand upon the worst problem, the fines would directly and indirectly cause air pollution problems at levels at or above state standards. The last fines to go through the stack cause a dusting problem in addition to changing the aggregate gradation in the mix. The fines carry burnt and unburnt asphalt out the stack with them. Finally and probably most crucial, fines would build up inside and eventually shut down the dryer because coarse (larger than 3/4 in.) material is not available in the mix to scour the insides of the drum dryer. These problems pinpointed by the manufacturer were sufficient for abandoning use of the drum dryer for the radon seal tests.

Chip Seal and Fog Seal

In our initial review of standard paving practice we covered the use of a chip seal and a fog seal and investigated their potential for applying a long-term radon seal. This review indicated neither system could be of use.

A description of problems associated with use of a fog seal is contained in last year's annual report (Hartley et al. 1980). Mention is made now of the major problem as it relates to the subsequent discussion. The inhibiting problem with fog seals is their inherently poor mechanical stability. These thin, 0.6 cm to 0.95 cm, membranes can fracture whenever overburden is applied. As overburden is necessary to protect the asphalt from ultraviolet light, this is a limiting factor.

A chip seal has many of the advantages of fog seals and few of the disadvantages. The basic feature is the addition of aggregate to give strength. A fog seal is initially applied over the tailings. Following this a calibrated volume of aggregate is applied by a chipper truck. This in turn is coated with asphalt by a fog spray. This process continues until the required depth and/or asphalt content is obtained. The final mixture is then compacted when 1) optimum temperature is obtained for hot asphalt or 2) enough water has left the system with asphalt emulsions.

This process is fast and inexpensive and does not require specialized equipment or manpower. Unfortunately, we concluded that several problems would occur. There would really be no mixing; a layered seal would result. Particle coating would vary significantly and, on the average, would be poor. These factors are important and detrimental to freeze-thaw resistance. As part of the control problem, run-off would be hard to control as would seal depth. These significant problems indicated we should abandon this approach.

Blade Mixing - Windrowing

Another standard asphalt paving practice considered useful, especially in remote areas, is the windrowing technique. Rows of aggregate are sprayed with asphalt emulsion in several passes by a distributor truck and then mixed by a motor grader blade. The spraying and mixing sequence continues until the required asphalt content is obtained. Closer examination of this technique indicated it was not worth pursuing. With the lack of control and the variability in mixing throughout the material, particle coating would be expected to be poor, runoff would be high, and problems of particle agglomeration would be encountered.

Batch Plant

In the asphalt paving industry, the central batch plant is generally used with hot mixes in urban or suburban locations. The batch plant consists of an aggregate preparation system that weighs the aggregate by separate gradations (see Figure 24). The aggregate is dumped into a top-entering pugmill with two horizontal shafts, each with a number of 15-cm-dia paddles. The pugmill, whose capacities are available from 2- to 5-ton batches, mixes the aggregate for a few seconds before dropping the asphalt into the batch. At the desired mixing time (~30 s) the admixture is dumped into a transport truck through a bottom gate designed for immediate discharge.

Central batch plants generally are not used for mixing asphalt emulsions. Continuous mixers offer more control of the mixing times which are so critical for emulsions (10 to 15 s for CMS, 20 to 30 s for CSS) by adjusting the spray bar location (Huffman 1976). Also, the central batch plant would create transportation problems of the admixture such as segregation of aggregate and asphalt, premature breaking, and stickiness, especially if the trailings

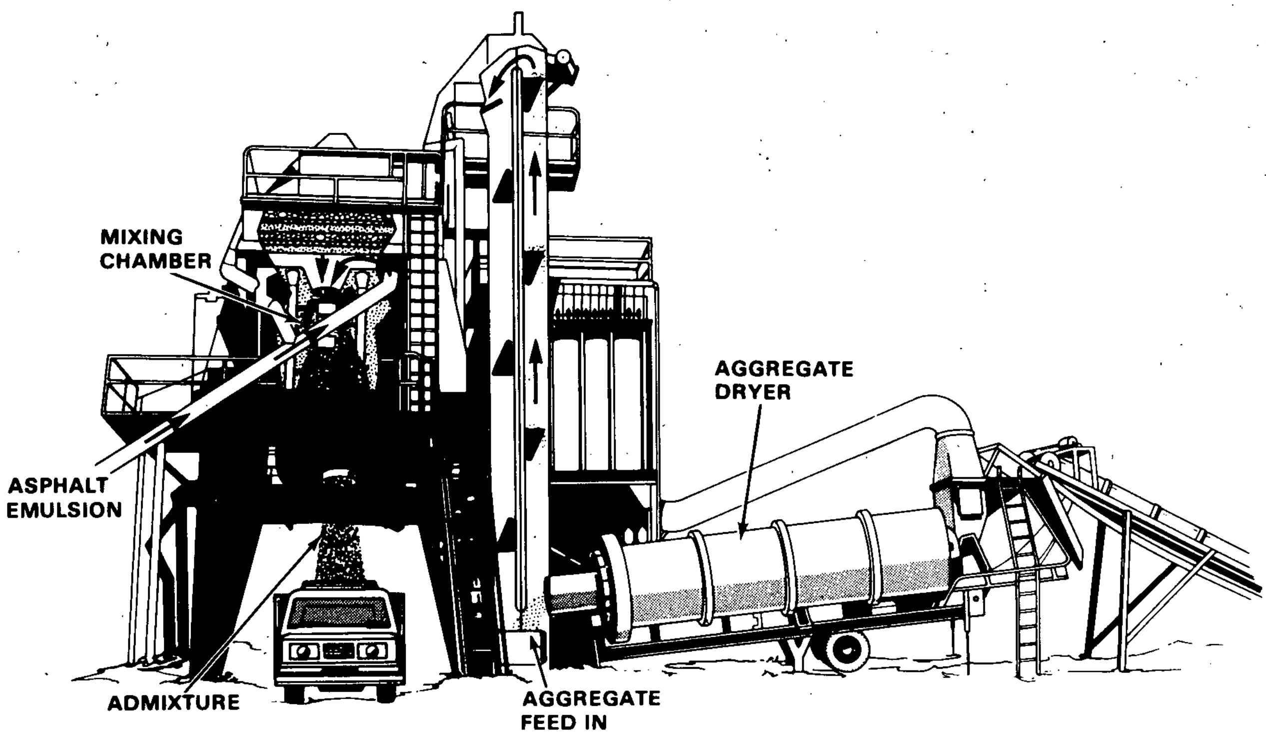


FIGURE 24. Typical Asphalt Batch Plant

disposal site was located in a remote area. The continuous portable pugmill was thus chosen for field testing instead of the central batch plant.

<u>Pneumatic Gun</u>

The pneumatic gun is used primarily in the industry to spray concretes for general construction and erosion control, but it has also been considered for use in asphalt paving patchwork with asphalt emulsions (Multi-Gunite Co. 1969). Adapting it to radon cover technology, the pneumatic gun would apply layers of an emulsion and fine aggregate mixture at high pressures that would probably not require compaction.

A pneumatic gun entrains granular materials into a compressed air stream, transporting them to a nozzle from which they are applied at high velocity to the application surface (Reed Mfg. 1977a). Two types of operation were considered for radon cover technology--the process that injects and mixes asphalt emulsion at the nozzle, and the process that entrains a premixed combination of emulsion and aggregate. Figure 25 is a schematic of the pneumatic gun process.

The material, whether it be dry aggregate (less than 8 wt% moisture) or the admixture, is fed into the hopper with a rotating agitator. The material falls into a series of feed bowls which are rotated by an air-driven motor. The rubber pad above the U-shaped feed bowls and the wear plate provide an airtight seal when the bowls pass under the air inlet. The air, provided by a compressor at 690 kPa (100 psi) and 10 $m^3$/min (365 cfm), forces the material into the transfer hose at high velocity.

Each of the two types of applications for radon covers has its own advantages and drawbacks. Though not tested for a pneumatic gun, a slow-breaking emulsion such as CSS would be required for the premixed process to reduce expected problems with material flow in the hopper and transfer hose. If the application surface were sloped, however, slumping of the admixture would be a problem. These problems are overcome with a rapidly breaking emulsion injected at the nozzle. Here the dry aggregate mixes with the emulsion and quickly

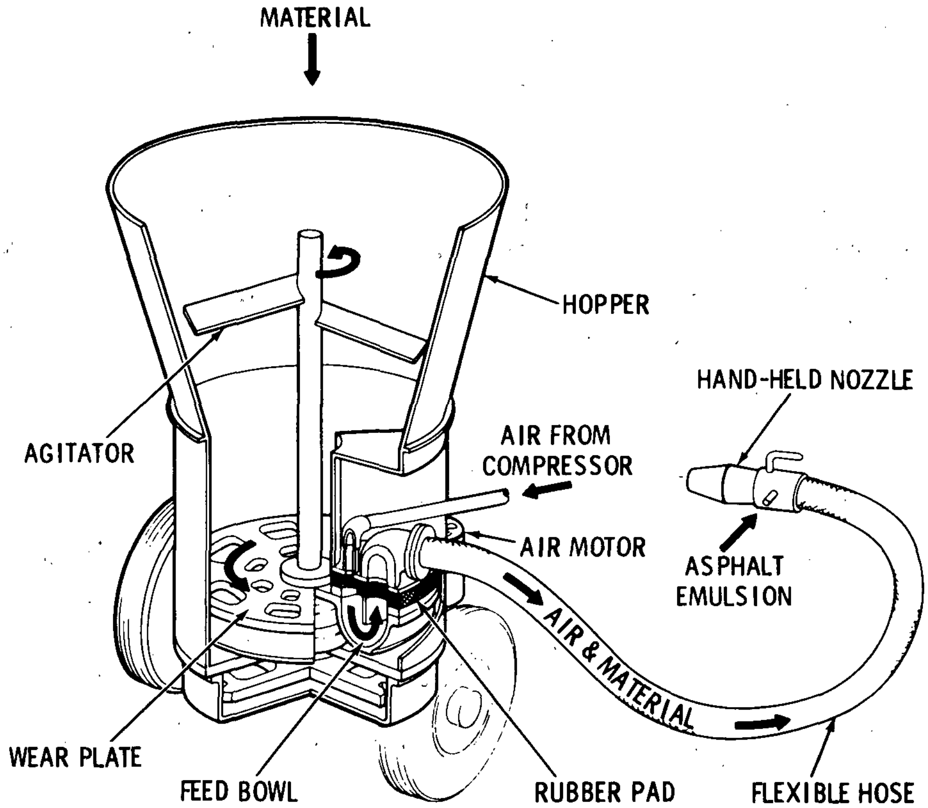


FIGURE 25. Pneumatic Gun

breaks on the application surface. Multiple layers would prevent slumping and allow water to run off without compaction. The mixing process may not be adequate for coating of the particles.

Under the best conditions, the pneumatic gun can produce 7 $m^3$ admixture per hour (Reed Mfg. 1977b). For comparison at a 7.6-cm radon seal depth the soil stabilizer can apply 96 $m^3$/h. Because a negligible reduction in manpower is realized with pneumatic gun and the gun needs a compressor to fulfill the air-requirements already mentioned, it is not economically feasible to use the pneumatic gun to apply radon seals. It is designed for patchwork and repair. While it was estimated for field testing in Grand Junction, its effectiveness should be evaluated in the field if a need is identified for seal repair or application on sloped surfaces that cannot be met by more conventional methods.

## 1980 GRAND JUNCTION FIELD TEST

The field test was conducted in August and September 1980 at the tailings site in Grand Junction Colorado. The field tests consisted of

- site preparation (contouring and base stabilization)
- seal application
- reclamation (overburden, revegetation, and biobarrier application).

## SITE PREPARATION

A 76.2-m x 76.2-m (250-ft x 250-ft) site was prepared for seal application by removing 5 to 30 cm (2 to 12 in.) of overburden cover then contouring the site for drainage. The test site was then watered and compacted to attain maximum density. Figure 26 shows an aerial view of the test area during site preparation.

Overburden was removed in order to expose the tailings for seal application. Overburden removal consisted first of removing irrigation pipelines on the site. Next, paddle wheel scrapers were used to remove the 5- to 30-cm

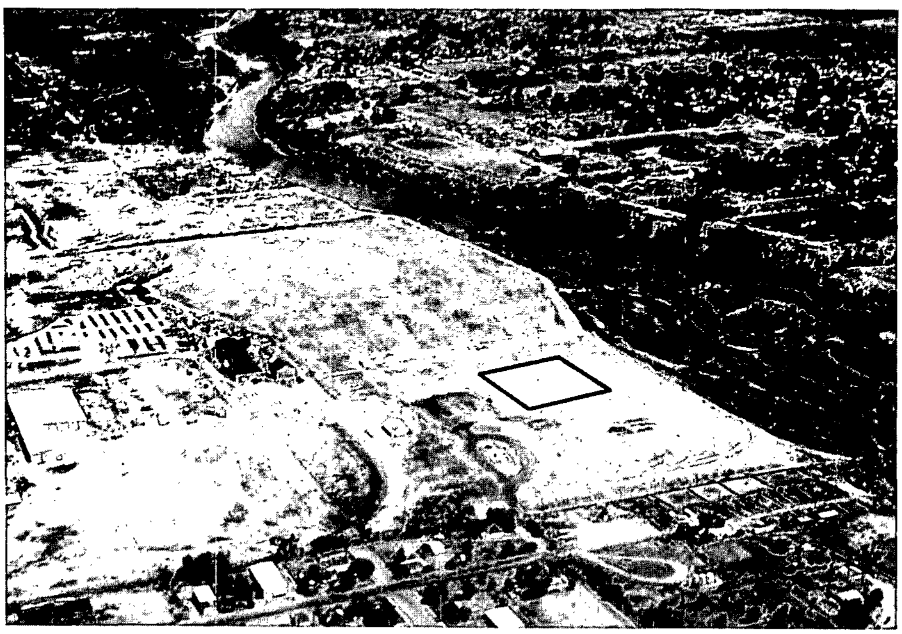

FIGURE 26. Aerial View of Grand Junction Tailings Pile Test Area

overburden on the tailings (see Figure 27). The site was then contoured to provide drainage to the northwest corner of the site and provide a fairly flat surface on which to apply the seal.

Next, the test site was staked out and radon measurements were taken. (These measurements will be discussed in a forthcoming section.) The site was then ready for stabilization efforts.

As previously mentioned, site stabilization was necessary for seal stability and supporting equipment during operation. The amount of stabilization necessary to support the cold-mix paver became the minimum stabilization criteria. Since some of the UMTRA tailings piles presently have no cover material locally available, let alone on them, special effort was made to use tailings as the stabilized base rather than haul locally available material onsite. Standard soil stability tests performed on these tailings (see Appendix C) indicated the tailings could be stabilized to support the cold-mix paver. This stabilization effort was designed with asphalt emulsion in mind since the emulsion would be readily available at sites sealed by our system. At Grand

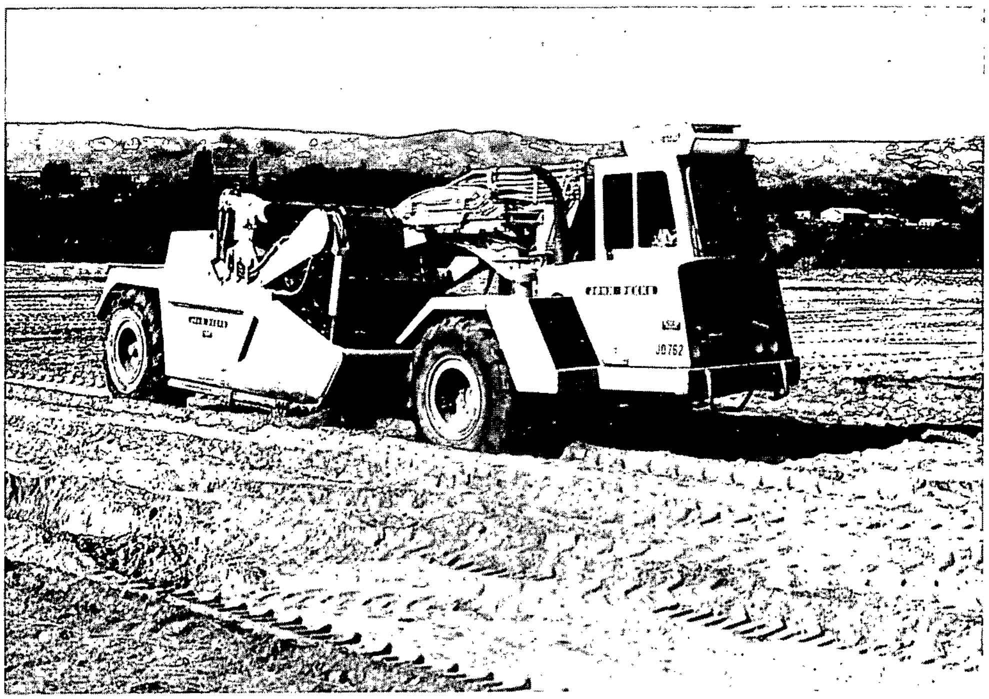

FIGURE 27. Paddle Wheel Scraper Removing Soil Cover From Test Area

Junction and at many other tailings sites it may be more cost effective to use the locally available aggregate for stabilization.

A 5-wt% residual asphalt was applied using a soil stabilizer (see Figure 28) to a 10-cm (4-in.) depth in watered areas (~8 wt% water) where the cold-mix paver, continuous pugmill and transit mix truck seals were to be used. This 65.9-m x 76.2-m (219-ft x 250-ft) area was then compacted (see Figure 29) to maintain density and strength. The site was then ready for testing of the sealing procedure.

The basic stabilization procedure consisted of watering, compacting, and asphalt emulsion application. The tailings were watered thoroughly with a water truck to achieve a minimum of 8% water in the tailings. The water

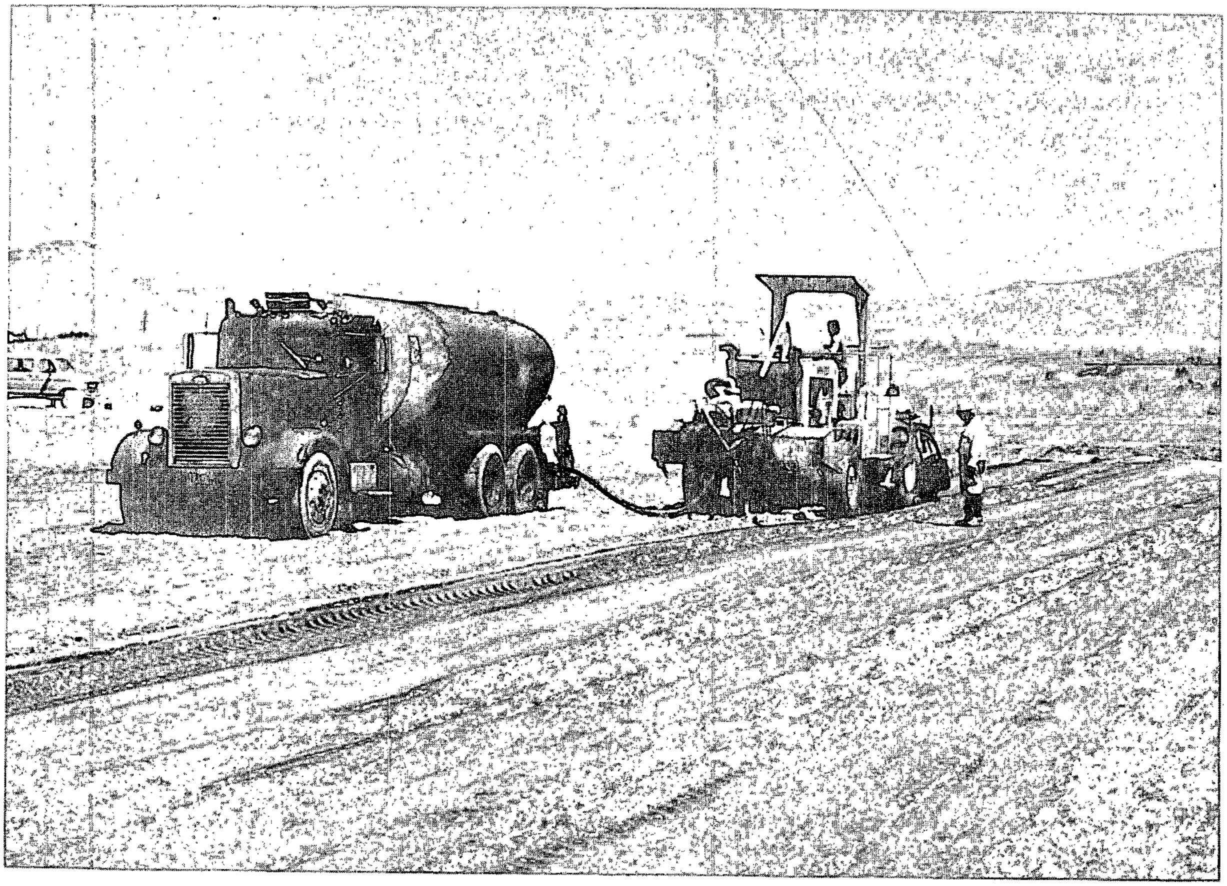

FIGURE 28. Soil Stabilizers Applying 5% Asphalt to Test Area

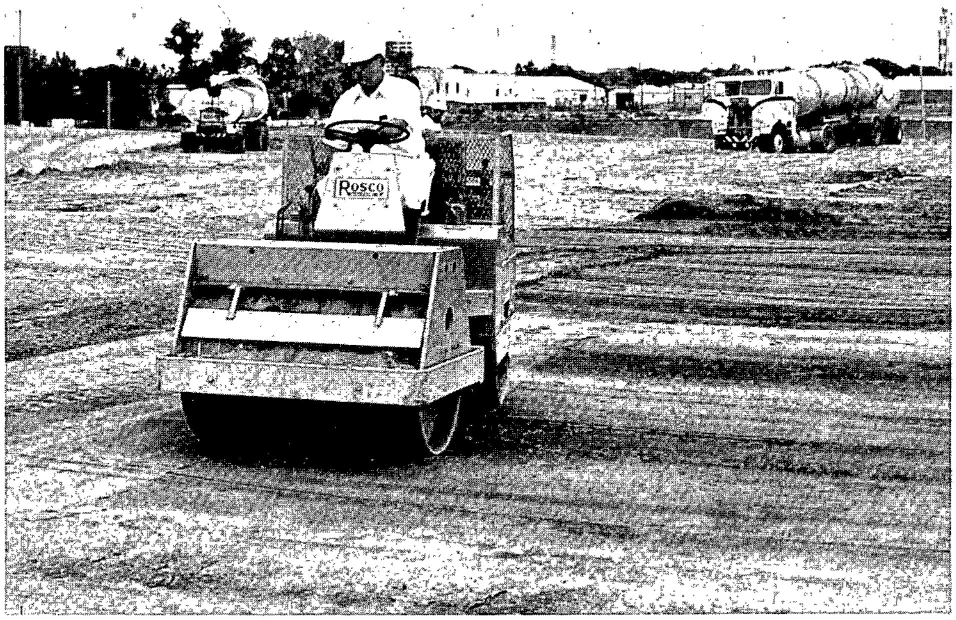


FIGURE 29. Vibratory Compaction of Tailings Containing 5 wt% Asphalt

content was monitored with a Speedy® moisture meter. The wet tailings were then compacted with a large eight-tire tractor.

The asphalt application was accomplished with a hydrostatically driven soil stabilizer hooked in tandem with a distributor truck (see Figure 28). To obtain the 5 wt% asphalt desired, it was determined the soil stabilizer must mix to a depth of approximately 6 in., move at a rate of 40 ft/min, and pump 87 gal of emulsion per minute. In actual application we achieved 5 to 6 in. of depth, 38.6 ft/min, and 87 gal of emulsion per minute. This data shows that the study objectives were met. To cover the desired area a total of 31 passes were made.

No major problems were encountered during the site stabilization. However, there were several small problems that arose. First, the distributor truck got stuck in the tailings several times and required towing. This illustrates how difficult it is to compact even wet tailings of the narrow size

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range that were encountered. A second problem was the depth of the soil stabilizer blade, which had to be monitored constantly in order to obtain a uniform depth. The hood over the blades tended to sink into the tailings, resulting in the blades digging in too deeply. Close monitoring enabled manual correction of this sinking in.

The asphalt tailings mixture was allowed to dehydrate for several hours and then was compacted with a 20-t front loader followed by a 5-t vibratory roller. A satisfactory stabilized base was obtained with this procedure.

## SEAL APPLICATION

Seal application was the most involved task with the following commercial application equipment: 1) a soil stabilizer, 2) a cold-mix paver, 3) a pugmill and paver, and 4) a transit mixer. In addition, three other spray-on application techniques were tested: 1) a multilayer sand seal applied with a distributor truck and chipper, 2) a fog (sprayed on) seal, and 3) a rubberized asphalt seal applied with a distributor truck.

Before the installation of the radon seal application, equipment was calibrated and prepared for optimum operation. This included performing necessary equipment modifications and preliminary test runs outside the test area. These efforts are described in the following field test discussions. A graphical representation of the sealed test site is shown in Figure 30.

### Soil Stabilizer

The objective of the soil stabilizer field test was to evaluate the use of a hydrostatically driven soil stabilizer to apply asphalt emulsion directly to uranium mill tailings and, when compacted, to form a radon-tight seal. The specific objective was to form an admixture of tailings and asphalt emulsion (~22 wt% residual asphalt) in a test area 9.5 m x 76.2 m (31.3 ft x 250 ft) to form a radon-tight seal.

The first seal application technique involved applying the ~22 residual wt% asphalt all in one pass. First, the soil stabilizer was run through the test area to mix the water and tailings uniformly. The distributor truck was hooked up to the soil stabilizer, and the asphalt emulsion was applied (see

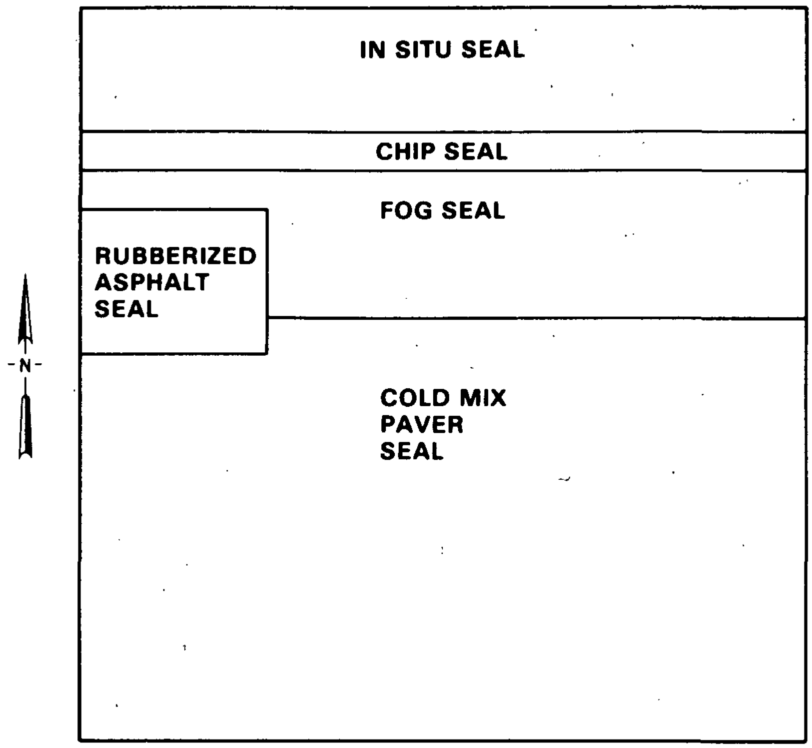


FIGURE 30. Seal Application Test Locations

Figure 31). After the soil stabilizer had traveled 38 m (~125 ft) the test was stopped. It was apparent at this point that the emulsion and tailings were not being uniformly mixed. In addition a streak was observed where no asphalt emulsion had been mixed with the tailings. The cause of this was thought to be a clogged nozzle. After this experience it was decided a multipass application technique was more suitable. This multipass technique consisted of the following steps:

1) mix water and tailings with soil stabilizer
2) apply ~7 wt% asphalt to tailings
3) remix asphalt-tailings mixture with soil stabilizer (no asphalt addition)
4) apply additional 7% asphalt to tailings
5) repeat step 3 until tailings-asphalt mixture looks uniform in composition.
6) repeat step 2
7) repeat step 3.

FIGURE 31. Application of 22 wt% Residual Asphalt to Grand Junction Tailings

The multipass system seemed to work quite well. Most of the tailings were well coated and the asphalt was well distributed within the tailings. Some buck shotting of the asphalt did occur in areas that did not have enough water, but these areas were limited in number.

Depth of mixing was controlled mainly by the density of the base being sealed. In some areas the tailings were mostly hard silty slimes. In fact, they were so hard that it made it difficult to mix down to the 5- to 6-in. depth desired. Other areas consisted of loose sands that tended to shift under the weight of the soil stabilizer, causing it to sink and mix deeper in the tailings. Depth control and mixing are the major concerns in determining whether a soil stabilizer is a suitable technique for applying a seal.

After the ~22 wt% asphalt had been applied, the mixture was allowed to dehydrate for one day before it was rolled. The compaction of the admix consisted of using a tractor, a 20-ton front loader, rubber-tired roller, and a

5-ton vibratory roller. The tractor and loader were not effective in compacting the admixture. When the temperature was cool, the tractor and loader did not compact the hard surface. When the temperature warmed up and the seal became soft, the admixture was pushed out under the tires and was not compacted. The rubber-tired and vibratory rollers were more successful in compacting the admixtures. However, their effectiveness was also greatly governed by the temperature of the seal. At cooler temperatures, much rolling produced moderate compaction. At higher temperatures both rollers easily became stuck in the seal. Extensive rolling eventually produced a seal that was 4 to 6 in. in depth. A photograph of the rolled seal is shown in Figure 32. It was concluded that there is a small temperature range in which rolling can take

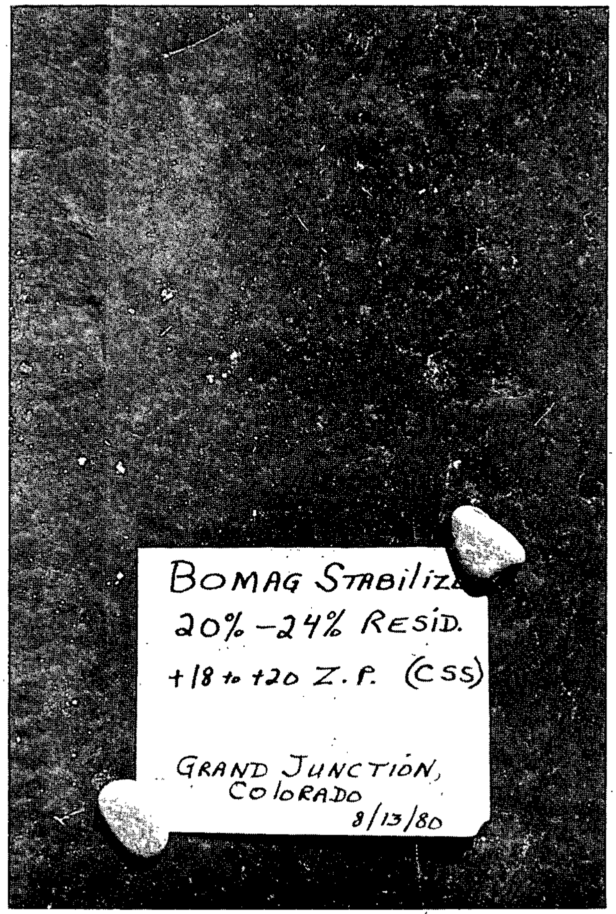


FIGURE 32. Compacted Seal Containing 20 to 24 wt% Residual Asphalt

place. Any rolling outside this temperature range is either nonproductive or destructive to the integrity of the seal.

Cold-Mix Paver

Testing of the cold-mix paver involved paving an admix seal consisting of +78 mV asphalt emulsion and concrete sand over a 28-m x 76-m (94-ft x 250-ft) area of the test plot. The following was observed during application of the seal:

- the operation of the cold-mix paver on stabilized tailings
- the physical characteristics of the admix after application and of the compaction
- the compaction characteristic of the admix
- joint formation.

The equipment screening tests identified several problem areas that required attention before the cold-mix paver was ready to use on tailings:

- Wider front support wheels (0.61 m) were installed on the paver to improve its off-road support on loose terrain.
- The aggregate feed rate was reduced 80% thus allowing the cold-mix paver to mix concrete sand and asphalt emulsion with 24 wt% residual asphalt. This feedrate reduction also improved feedrate control.
- Slip-form skids were added to the bottom of the screed (admixture spreading unit) to help the screed maintain the proper uncompacted admixture depth (10 cm).

Following these minor modifications, the asphalt emulsion pump and aggregate feed rate were calibrated. The asphalt emulsion pump was calibrated by pumping asphalt emulsion from the cold-mix paver into a pre-weighed tanker at various feed rates. Duplicate tests indicated that the pump was accurate to within $\pm 0.5\%$ when values were corrected for emulsion temperature-volume variations. Asphalt emulsion at $60^{\circ}C$ was used during the test. Visual readings of the flow meter thus only needed temperature-volume corrections to determine actual emulsion flow rates.

Calibration of the aggregate feed rate was accomplished by using a pre-weighted aggregate passing through the pugmill at different aggregate feed gate settings. The tests indicated the maximum gate opening, 13 cm, was compatible with the required asphalt emulsion pumping rates. Approximately 1044 kg/min (2300 lbs/min) of aggregate is needed to match the 380-L/min (100.4-gal/min) asphalt emulsion needed to obtain the desired 24 residual wt% asphalt. This assumes 62 wt% asphalt in the emulsion and a specific gravity of 1.0 at 15°C (Asphalt Institute 1979a).

The cold-mix paver was initially operated at the desired settings in an area outside the test plot as a final check to insure proper operation. We used these test runs to review operation of the cold-mix paver and to evaluate the admix characteristics. We also roughly confirmed that asphalt emulsion and aggregate consumption rates were within expected limits. Two test runs were made at asphalt emulsion flowrates of 390 and 360 L/min (103 and 95 gal/min), respectively (corrected for temperature at 54°C). The first run revealed no significant operating problems except for excessive runoff of asphalt emulsion from the seal. This condition was corrected during the second run at the lower flow rate. Because of inherent fluctuations in flow meter readings the average value observed was used. The cold-mix paver was then ready to apply an admix on the test plot.

The first seal application effort with the cold-mix paver covered, as planned, a 25-m x 76-m (84-ft x 250-ft) area with an admix layer averaging 8.4 cm (3.3 in.) in uncompacted depth (see Figures 33 and 34). The admix, composed of +73 mV CMS-1 cationic asphalt emulsion and concrete sand (see Table 3), was applied on top of a 5.0-cm-thick compacted -3/4-in. road base material. Road base was placed on the asphalt stabilized base to further stabilize the base for this very heavy 40-ton machine. Asphalt emulsion temperature before entering the cold-mix paver pugmill varied from 42°C to 54°C, and aggregate temperature below the surface of the aggregate stock pile averaged 26°C with ambient temperature registering 28°C. Aggregate moisture content was about 4 wt%.

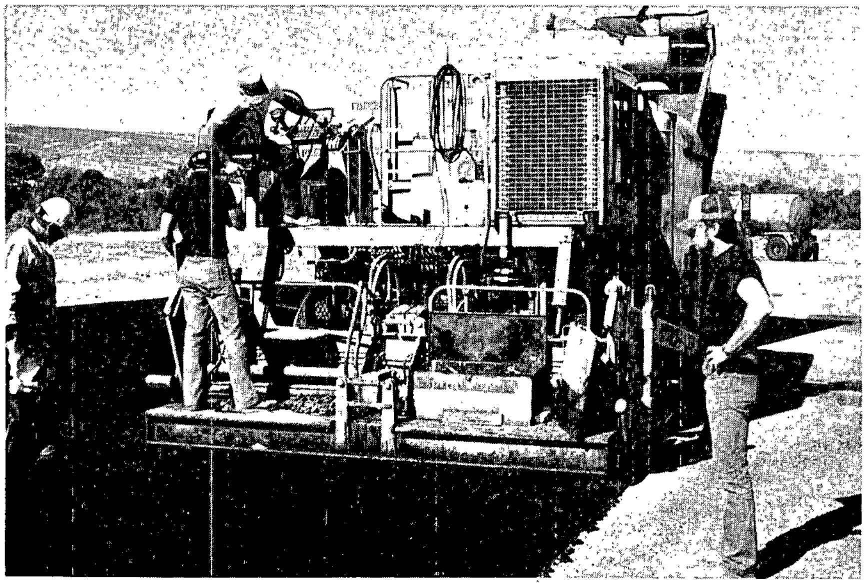

FIGURE 33. Cold-Mix Paver Applying Admix Seal

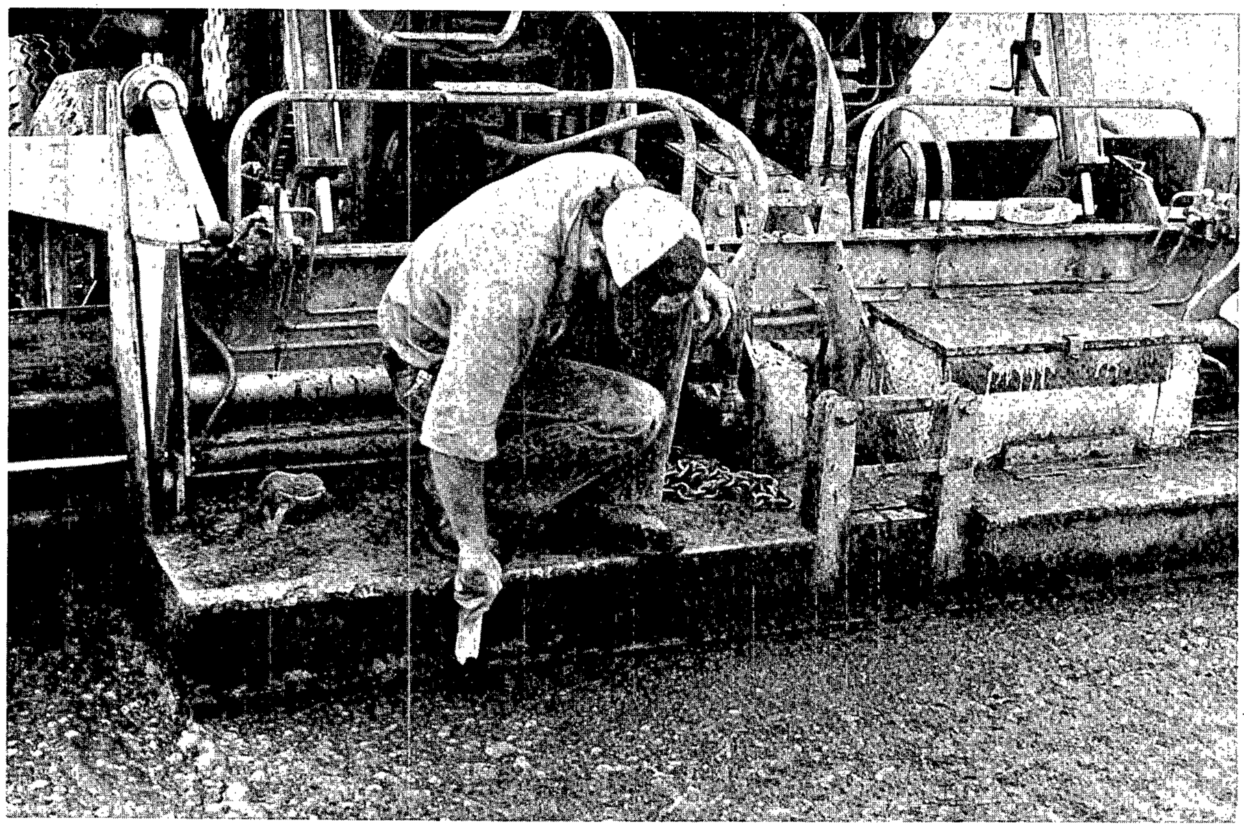

FIGURE 34. Cold-Mix Paver--Closeup of Seal Application

The second seal application effort was undertaken because of problems associated with the sealing technique using the continuous pugmill. As discussed further in a subsequent section, 1) several thousand gallons of asphalt emulsion were onsite which had to be used, 2) we were committed by contract to use several thousand more, and 3) one-third of the test plot was still unsealed. For these reasons the cold-mix paver was used to cover more of the test plot with a successful seal. The second application covered an area 20 m x 76 m (67 x 250 ft) with the admix-seal uncompacted depth varying from 10 to 18 cm (4 to 7 in.). (Refer to Figure 30 for location.) The admix seal in this test run was composed of three different cationic asphalt emulsions:

- +70 to +75 mV CMS-1 (manufactured the day before its use and at 50$^{o}$C to 56$^{o}$C in the cold-mix paver tank)
- +54 to +58 mV CMS/CSS-1 (manufactured 2 days before its use and at 37$^{o}$C to 43$^{o}$C in the cold-mix paver tank)
- +70 to +75 mV CMS-1 (manufactured 3 days before its attempted use and at approximately 42$^{o}$C)

The admix was also applied over 5 to 7.6 cm (2 to 3 in.) of compacted -3/4 in. road base material. The concrete sand used within the admix averaged 5% moisture in the stock pile and had an average below-surface temperature of 23$^{o}$C.

Both of these application efforts went fairly smoothly, and, with one exception, the problems encountered were common to both application runs. The first major problem concerned the quality control on the +78 mV CMS asphalt emulsion. Approximately 56.7 kL (15,000 gal) of the 105.8 kL (28,000 gal) of the CMS asphalt emulsion initially delivered was returned to the manufactuer as defective (see Figure 35).

The +70 to +80 mV CMS-1 asphalt emulsion made up a desirable admix seal. The admix produced in the cold-mix paver pugmill was viscous, somewhat more fluid than molasses. It spread evenly underneath the screed and provided smoothly lapped joints (see Figure 36). The admix set-up approximately 9 m (30 ft) behind the cold-mix paver, slumping from its paved dimensions about 10%; a 3-m wide by 10-cm deep (3-ft by 4-in.) seal laid by the cold-mix paver

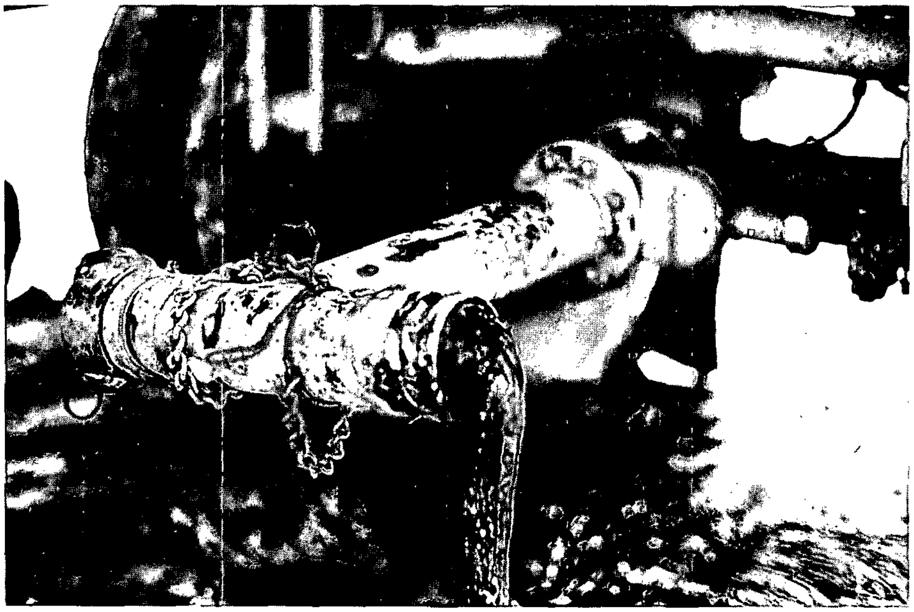

FIGURE 35. Defective Asphalt Emulsion Draining Out of Tanker

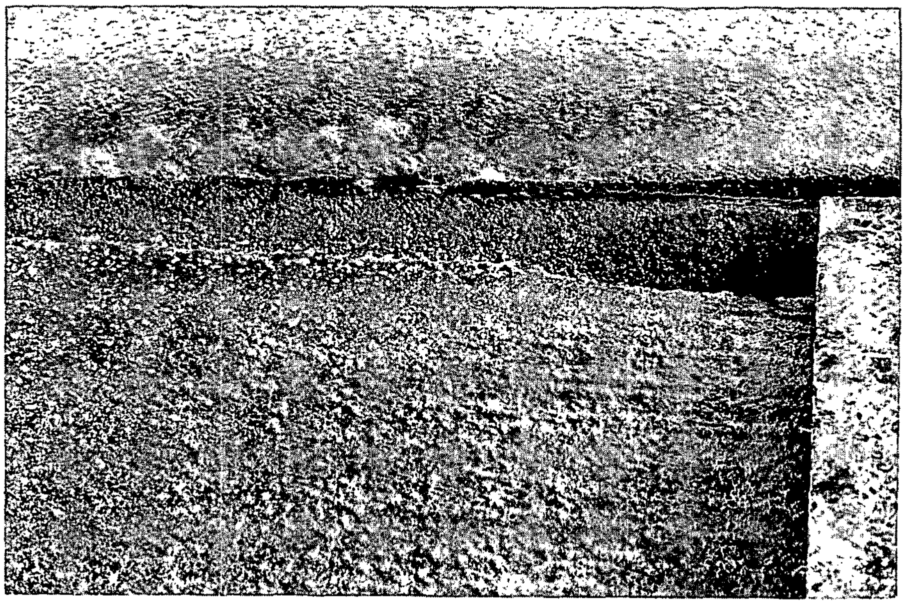

FIGURE 36. Admix Rapidly Seals Over Joint Immediately Behind Slip Form Screed

became 3.3 m (11 ft) by approximately 8.3 to 9.4 cm (3.1 to 3.3 in.) deep (see Figure 37). The asphalt emulsion manufacturer, unknown to him and to our benefit, made the CMS with 66 residual wt% asphalt instead of the specified 62% and this higher asphalt more than compensated for the minor amount of runoff encountered.

The newly manufactured +73 mV CMS used in the second run acted stiffer than the emulsion in the first run even though it retained most of the same desirable characteristics. Joints did require a little more care to insure a proper overlap of 15 cm (6 in.).

Even so, the desirable characteristics of the admix seal easily allowed an average production rate of 800 $yd^2/h$ during the first seal applicaton run. This includes time for batch loading of the asphalt emulsion tank on the cold-mix paver. An average production rate of 370 $yd^2/h$ was obtained during the

FIGURE 37. Typical Admix Slumping Encountered in Seal Application

second seal application run because of a break in work for a passing thunderstorm and other circumstances discussed below.

The asphalt emulsions used for the remainder of the second application run were troublesome. With the 3-day-old +73 mV CMS asphalt emulsion originally tried in the continuous pugmill test, the cold-mix paver could not pave a continuous seal. The viscid admix, once out of the pugmill, was pulled apart by the dragging screed. We discontinued trying to make a seal with this material after an unsuccessful 20-m (67-ft) attempt.

The +54 mV CMS/CSS admixture also was difficult to use but was acceptable when paved at 20 cm (8 in.) uncompacted depth. We took special care to insure proper joints with this material but still had to repair minor imperfections in the joints later on. We are not sure why the admixtures were excessively stiff on the second run. The only parameters tending to cause an asphalt emulsion to break (stiffen up but not to the extent encountered) were 1) slightly cooler ambient temperature of $19^{O}C$ to $20^{O}C$, 2) slightly cooler emulsion temperatures, approximately $42^{O}C$, and 3) a slow evaporative breeze. The parameters that should had led to a far more fluid mix were:

- higher humidity (In fact, we had to take a 45-min break to let a thunderstorm pass over.)
- changed moisture content (a slightly higher, 1%, moisture content in the aggregate)
- Lower zeta potential (CMS/CSS admix should have been too fluid because lower zeta potential dictates it should break more slowly than CMS emulsion.)

Also, +73 mV CMS-1 asphalt emulsion was applied at the lower asphalt emulsion temperature during the first run with no problems.

The zeta potentials of the emulsion used on the second run are being checked but at this point we can only use the incident as an example of quality control or weather problems that could be encountered in applying an asphalt seal. This suggests that other means of control are needed to compensate for environmental conditions.

The second major problem dealt with the ground preparation required to support the cold-mix paver. Even though the stabilization of the tailings with the asphalt emulsion was sufficient to support the loaded (asphalt emulsion and aggregate) cold-mix paver, it was not sufficient to withstand the sudden dynamic loads inflicted when aggregate is initially dumped from a dump truck into the storage bin on the cold-mix paver. During the first pass, the front wheels immediately penetrated the prepared base when the second load of aggregate was dumped into the storage bin. Since the situation became progressively worse, the run was discontinued before the cold-mix paver high-centered. Five to 7.6 cm (2 to 3 in.) of 2-cm -3/4-in. crushed road base were applied over the tailings and compacted, which easily supported the cold-mix paver.

The third major problem involved the functioning of the cold-mix paver admixture spreading unit, or screed as it is commonly called. We recognized that this screed was not designed for use with the fluid mixes it encountered in our test. Our experience in the equipment screening test dictated adding skids. These skids, while suitable for supporting the screed on hard compacted clay were not useful on sandy materials like tailings. As they also interfered with good joint formation, they were modified during the test to leave slip forms for controlling the dimensions of the admix seal.

Slump of the admix seal was more than expected so the screed height had to be raised from the initial 9.2 cm (3.6 in.) to 13 cm (5 in.). This was later changed to 10 cm (4 in.) to handle the stiffer +73-mV CMS admixture and changed again with the use of the CMS/CSS admix. These varying screed heights above ground level were upheld by a hydraulic system that requires constant monitoring for depth control. We verified the screed height and thus the applied seal depth by regularly measuring the admix depth. Another symptom of this problem was the tendency of a freshly produced admix sloughing to one side of the screed on very minor slopes. This was caused by the screed not being specifically designed for fluid mixtures; it could be solved by changing the position of the augers that spread the admixtures from the pugmill center to the outer edge of the screed. This screed worked acceptably in the idealized situation; but the hydraulics, slumping, and slough in problems make it a major weakness. Research efforts should be directed at designing a spreading unit, such as a slip form, better suited to placing our admix characteristics.

On the other hand, no significant problems were encountered with the precision of the asphalt pumping or aggregate feed rate. Our modifications lowered the extent of the variances to beneath acceptable limits at the expense of the production rate of the cold-mix paver. When scale-up occurs it could again be a problem.

Actual installation of the seal is not complete until it is compacted. Compaction not only closes or seals off any interconnected voids but also helps squeeze out excess water remaining in the seal. We monitored the moisture and density to indicate the need for and progress of compaction. Using a theoretical 130 $lb/ft^3$ as maximum obtainable, the densities of uncompacted asphalt seals show a definite need for compaction (see Table 11). Moisture content of the uncompacted cold-mix paver seal two days after laydown showed approximately two-thirds of the water initially in the seal at laydown had drained away or evaporated (see Table 12). As compaction efforts rarely get moisture contents below 2% even in standard paving mixtures, compaction was needed to expel any further moisture.

The seal was compacted 4 to 10 days after the seals were applied with a 2.7- to 4.5-t (3- to 5-ton) vibratory and a 7.3-t (8-ton) static tandem roller. We staggered the amount of time allowed for the seal to dehydrate itself by evaporation and drainage in order to gather preliminary data on such effects. The moisture content of the compacted cold-mix paver seal 21 days after initial seal laydown indicated compaction only reduced moisture content by approximately 0.4%.

An attempt to follow compaction by coordinating density measurements with compactive effort was made, but this had to be abandoned when it was found that gamma radiation from the tailings interferred with the reading of the nuclear densimeter. Current data show densities of approximately 130 $lb/ft^3$ were obtained, but more data are needed.

In summary, compaction of the seal was probably initiated too soon as evidenced by the still relatively high moisture content of the seal. More substantial data is needed to characterize the compactive phase of seal formation. This can be acquired through laboratory studies and seal examination and sampling when possible in the spring.

TABLE 11. Physical Characteristics of Cold-mix Paver Seal

| Sample Site[a] | Date Asphalt Seal Applied | Date Sample Collected | Residual Asphalt[b] Content, wt% | Moisture[b] Content, % | Density,[c] $lb/ft^3$ |
|---|---|---|---|---|---|
| Strip 1 A | 8/13 | -- | -- | -- | 105 |
| B | | -- | -- | -- | 103 |
| Strip 2 A | 8/14 | 8/17 | 19.9 | 3.6 | 109 |
| B | 8/14 | -- | -- | -- | 110 |
| Strip 3 A | 8/18 | 8/20 | 23.4 | 3.8 | 112 |
| B | 8/14 | 8/17 | 21.9 | 3.7 | 104 |
| Strip 4 A | 8/18 | 8/20 | 23.4 | 4.0 | 103 |
| B | 8/18 | 8/20 | 23.0 | 4.4 | 103 |
| Strip 5 A | 8/18 | 8/20 | 23.4 | 4.7 | 102 |
| B | 8/18 | 8/20 | 23.4 | 4.7 | 101 |
| Strip 6 A | 8/18 | 8/20 | 24.2 | 4.1 | 102 |
| B | 8/18 | 8/20 | 23.8 | 4.1 | 99 |
| Strip 7 A | 8/18 | 8/20 | 24.7 | 3.5 | 101 |
| B | 8/18 | 8/20 | 23.8 | 3.5 | 99 |
| Cold-mix Paver 9A[d] | 8/18 | 9/8 | 22.2 | 3.7 | -- |
| Cold-mix Paver 11D[d] | 8/18 | 9/8 | 22.0 | 3.8 | -- |
| Cold-mix Paver 13A[d] | 8/23 | 9/8 | 22.9 | 4.7 | -- |
| Cold-mix Paver 13D[d] | 8/23 | 9/8 | 23.7 | 4.1 | -- |
| Cold-mix Paver | 8/23 | 9/8 | 28.4 | 4.6 | -- |

(a) The paving strips, which are about 3 m wide, start from the south side (running east to west) and go north (1-13D).
(b) Based on dry aggregate basis, i.e., wt asphalt/wt aggregate.
(c) Densities taken by nuclear densimeter in $lb/ft^3$.
(d) The samples were taken where radon measurements were made. Refer to Figure 53 for location.

TABLE 12. Aggregate Calibrations Runs For The Pugmill

| Calibration Run | Wet Aggregate Rate, kg/h | Dry Aggregate Rate, kg/h | Deviation, kg |
|---|---|---|---|
| #1 | 824 | 795 | 13 |
| #2 | 783 | 755 | 27 |
| #3 | -- | -- | -- |
| #4 | 824 | 794 | 12 |
| #5 | 857 | 826 | 44 |
| #6 | 823 | 794 | 12 |
| #7 | 756 | 729 | 53 |
| Average | 811 | 782 | 34[a] |

(a) Standard Deviation

## Continuous Portable Pugmill

The objective of the field test with the continuous pugmill (see Figure 38) was to evaluate the effectiveness of an asphalt-emulsion admixture prepared by the pugmill for attenuating radon flux from uranium mill tailings. An 8-cm layer was to be paved over the surface of a portion of the test plot area measuring 19 m x 76 m. Control parameters were evaluated for optimum seal application.

The field test was accomplished in four parts:

- material characterization, which determines moisture content, temperature, and other properties of the aggregate plus specifications of the asphalt emulsion
- equipment calibration, which through test runs calibrates the pugmill to obtain an admixture with 22 to 25 wt% residual asphalt on a dry aggregate basis
- trial paving runs, which experiments with asphalt content, retention time of the emulsion and aggregate in the pug, aggregate moisture content, aggregate electronegativity, and cationic potential of the asphalt for the most optimum seal application
- placement of radon seal on test plot area.

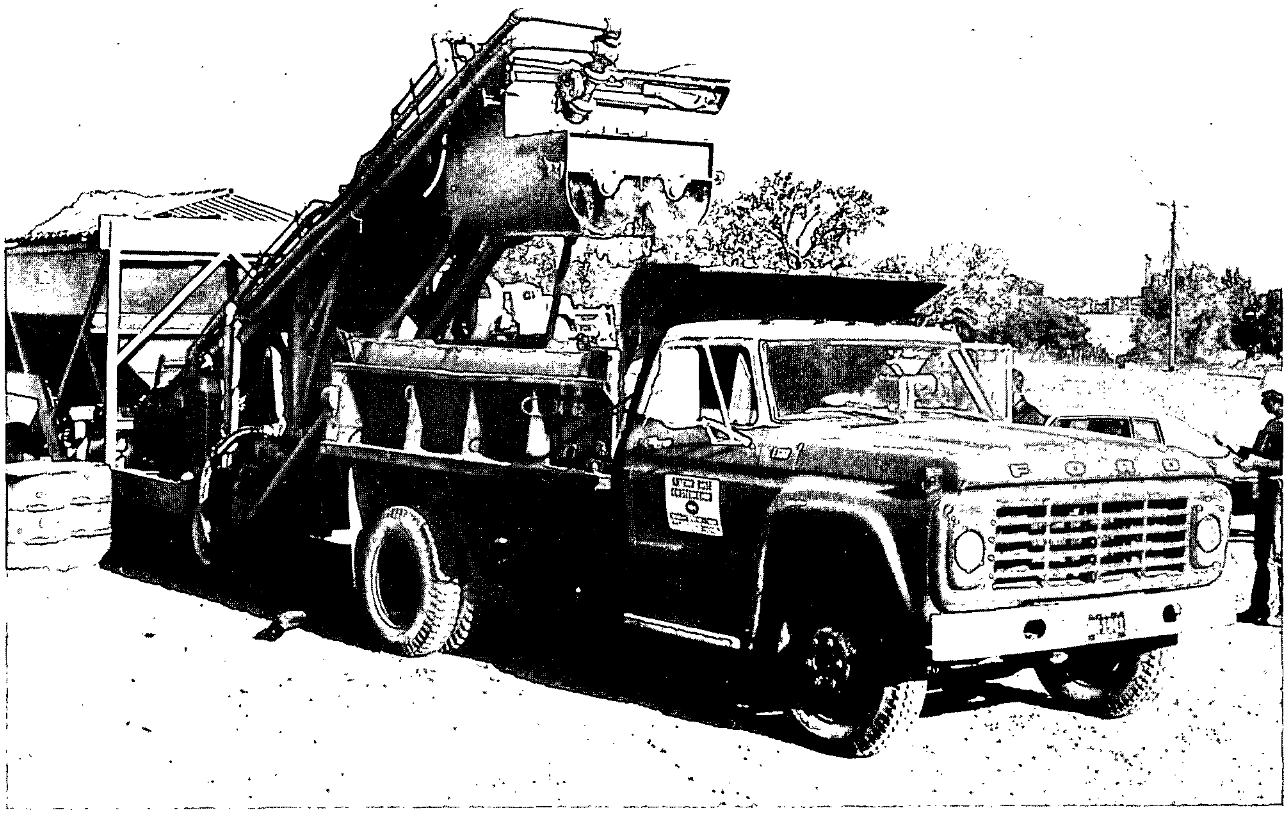


FIGURE 38. Continuous Portable Pugmill

Following the material characterization and calibration runs, the trial paving runs showed that the portable pugmill is not conducive to producing a workable admixture that can be paved as a radon seal. Experimenting with the previously mentioned control parameters, no reliable procedure could be identified that would keep the 25 wt% residual asphalt admixture from setting up in the transfer truck and would not allow the aggregate and asphalt emulsion to segregate.

Concrete sand is the best aggregate material for the radon seal as determined by the seal formulation studies. The size specifications used in the tests are listed in Table 3. Since all equipment calibrations are based on dry aggregate, the moisture content of the concrete sand was measured and found to be 3.6 wt%. Aggregate moisture is necessary since it acts as a dispersive and lubricating agent (Dybalski 1974). The aggregate temperature below the surface of the stockpile at mid-afternoon was 26°C, differing little from the 28°C ambient temperature.

Manufacturer's specifications for the asphalt emulsion state that the zeta potentials for the three emulsions used in the trial runs range from +18 mV to +80 mV. The designations for the three materials are:

- CMS--zeta potential of +76 to +80 mV
- CMS/CSS-1-h mix--zeta potential of +54 to +58 mV
- CSS-1h--zeta potential of +18 to +20 mV.

Because the data was not yet available, the asphalt content in the CMS emulsion was assumed to be 62 wt%, the same as the CSS emulsion. Since the researchers were unaware of the actual 66 wt% at the time, the CMS trial runs produced admixtures with residual asphalt content of 27% instead of the targeted 25%. This is of little consequence, however.

To assure the proper amount of residual asphalt necessary to impede radon diffusion through the seal, numerous aggregate and asphalt calibration runs were performed with the pugmill. At a constant minimum gate height of 7 cm through one side of the split bin and at a constant belt speed, the average dry aggregate flow was 780 kg/min. Individual calibration runs are listed in Table 12.

The desired asphalt content is 0.25 wt%. Assuming 62 wt% asphalt in the emulsion, and a specific gravity of 1.0 at 15°C (Asphalt Institute 1979a), the required amount of emulsion is 402 L emulsion/1000 kg (48.3 gal/1000 lb) of dry aggregate. Temperature corrections are given in Table 13, calculated from correction factors given by the Asphalt Institute (1979c).

The emulsion totalizer on the pugmill (readout in gallons) was calibrated with weigh scales. Using a stop watch, the average pump rate was 327 L/min (86.4 gpm). By the weigh scales, the average rate was 315 kg/min. Since the emulsion temperature was 53°C, the rate determined by the scales was 320 L/min. This is within experimental error, meaning the flow totalizer was well within the needed accuracy range for the test.

TABLE 13. Asphalt Emulsion Temperature-Volume Corrections

| Temperature, °C | Correction Factor | Asphalt Required Per 1000 kg Dry Aggregate (L) |
|---|---|---|
| 15 | 1.000 | 402 |
| 20 | 0.998 | 403 |
| 30 | 0.9935 | 405 |
| 40 | 0.989 | 406 |
| 50 | 0.9845 | 408 |
| 60 | 0.980 | 410 |
| 65 | 0.9778 | 411 |

Before applying a seal to the test plot area, trial paving strips had to be paved to determine the optimum paving conditions. Control parameters include aggregate moisture, asphalt content, zeta potential of the emulsion, aggregate electronegative charge, and retention time for mixing in the pugmill. Table 14 is a synopsis of the effect of those control parameters on performance.

The first control variable was aggregate moisture control. Besides affecting the setting rate (Asphalt Institute January 1979), the moisture in the aggregate acts as a lubricating and dispersive agent. With all other parameters constant, three trial runs with aggregate moistures of 3.6 wt%, 8.9 wt%, and 12.0 wt% were performed. The natural stockpile moisture content was 3.6 wt%; in the other two runs, water was added to the aggregate through the water spray bar before entering the pugmill. Unfortunately, aggregate moisture content helped very little in controlling the break time. The CMS emulsion used in this test had a strong positive zeta potential of 76 to 80 mV. Regardless of water content, the material could not be paved, even at a 13-cm depth, without tearing. Worse yet, the material would not easily slide out of the truck without being scraped, though some improvement was noted at the 12 wt% level.

TABLE 14. Effect of Pugmill Control Parameters on Performance

| Control Parameter | Control Data | Observations |
|---|---|---|
| 1) Aggregate moisture content (using CMS) | a. 3.6 wt% moisture content | a. Admixture stiff and difficult to pave |
| | b. 45 L/min water added for moisture content of 8.9 wt% | b. Admixture still too stiff to pave |
| | c. 76 L/h water added for moisture content of 12.0 wt% | c. Some improvement noted, but still too stiff |
| 2) Asphalt content (using CMS emulsion and 3.6 wt% aggregate moisture) | a. 320 L/h of emulsion added for 25% residual asphalt | a. Admixture too stiff to avoid tearing |
| | b. 400 L/h of emulsion added for 32% residual asphalt | b. Admixture set up much more quickly, forming stiff clumps |
| 3) Zeta potential of emulsion (using 3.6 wt% aggregate moisture and 25% residual asphalt) | a. CMS +76 to +80 mV | a. Admixture too stiff to pave |
| | b. CMS/CSS-1h mix +54 to 58 mV | b. Slight segregation; bottom of truckload rich in aggregate and stiff |
| | c. CSS-1h +18 to +20 mV | c. Great segregation; high runoff of asphalt; bottom of truck rich in aggregate and stiff |
| 4) Aggregate charge removal (using CMS/CSS mix) | a. 0.1 wt% $Al_2(SO_4)_3$ with 0.15 wt% $H_2SO_4$ for solubility added in water solution to aggregate before pugmill | a. Emulsion completely separated from aggregate in truck |
| 5) Pugmill retention time | a. Attempted to increase mixing time by adjusting deflection plate to maximum and reversing some paddles | a. Attempts unsuccessful; mean time between 5 and 10 s |

Since the material had an apparent "dryness," the next control variable was the asphalt emulsion content. Without adding any water to the aggregate, the emulsion additive rate was increased for a 32 wt% residual asphalt content on a dry aggregate basis. However, the increased number of asphalt particles with the high zeta potential combined more strongly with the aggregate to produce a stiffer mixture that formed clumps that would not pave. A logical progression, then, would be to decrease the asphalt content; however, the admix would then contain insufficient asphalt to produce a reliable radon seal, so this was not tested.

The asphalt emulsion when contacted with the aggregate broke too rapidly for the physical handling of the admixture and for transfer and paving. The next control variable tested to reduce this effect was decreasing the asphalt emulsion zeta potential. The breaking time would conceivably be increased so that the material would still flow from the truck through the paver and lay down in an even mat without tearing. However, with the CMS/CSS-1 h mixture (zeta potential at +54 to +58 mV), the aggregate segregated in the truck. Though the material flowed consistently and fluidly out of the pug, the top of the mixture in the truck was light in aggregate; the bottom was stocky and difficult to remove and pave. Pure CSS emulsion (zeta potential between +18 to +20 mV) separated from the aggregate allowing the residual asphalt in the aggregate to be less than that required for a radon seal.

Another method of slowing the breaking time is to reduce the electronegativity of the aggregate. Adding 0.1 wt% $Al_2(SO_4)_3$ with 0.15 wt% $H_2SO_4$ for solubility would allow the positive aluminum ion to combine with the aggregate before entering the pugmill. Experiments with the emulsion mixture of a zeta potential between +54 and +58 mV showed the effects to be dramatic. Even with the slightest attainable addition rate of $Al_2(SO_4)_3$, the asphalt did not break to the aggregate, causing noticeably more aggregate segregation. This allowed the asphalt to run off. Evidently, electronegativity control of the aggregate is difficult for this application in the field.

The only other recourse for testing the pugmill for radon seal application was to extend the retention time of the admixture in the pugmill in hopes the asphalt would more completely break to the aggregate before transfer to the dump truck. This was attempted by adjusting the aggregate deflector plate, increasing the mixing rate by a factor of 1.6 to more completely fill the pug, and reversing some of the paddles in the pug for reverse flow. These variables were tested with different emulsion types, still with no noticeable success. From the time the mixture was introduced to the pug, the first material would exit in 5 s. Reversing the paddles would evidently provide the best retention time control, but the number of reversed paddles was limited by the pugmill's shear pin capacity.

All attempts at different controllable parameters were unsuccessful in applying a reliable radon seal. The primary difficulty was in attaining a mixture with the required residual asphalt content that would break quickly enough to avoid liquid separation and would still be workable enough for transfer or paving. The key factor, which indicated the pugmill would be the most viable option based on the screening tests before Grand Junction, is asphalt content. In Eugene, Oregon, the admixture attained was only 12 to 13 wt% as indicated by subsequent measurements. Results from this study show that for CMS emulsions the more asphalt in the admixture (up to 32%) the more handling problems. The lack of hydrocarbon solvent in the emulsion may also play an important role in that regard.

One parameter that was not tested here is asphalt temperature. A reduction in asphalt temperature will slow breaking time, but temperature reduction makes the admixture stiffer. Provided the pugmill can accommodate the extra strain, a reduction in temperature may have helped solve the problem. However, due to temperature control problems in the field, emulsion temperature was not considered as a control parameter.

Transit Mixer

Four test mixes were attempted in a old transit mix truck with a capacity of about 4.6 $m^3$ (6 $yd^3$). Drum rotation was very slow but most likely was not a factor in the outcome. All sand and emulsion admixture components were weighed; water was added by volume determination.

The first test consisted of adding 53 L water and 756 L Armak +78 mV emulsion to 1.1 t concrete sand in the drum. The mixture was mixed for 10 min and then dumped. The admixture appeared similar to a laboratory admixture during mixing but segregated upon reversing the drum for offloading. This resulted in a water phase and large lumps of admixture (see Figure 39).

The second test was identical to the first except the mixing time was reduced to 60 s in an attempt to create a more fluid mixture. No improvement in admixture quality from the first test was observed. Upon reversing the drum for offloading, the water phase separated and lumps began to form. Lumps were smaller than the first ones, but the separated admixture was obviously unsuitable as paver feedstock.

In the third test, Armak 4868 emulsion (+18 mV) was used to slow down the setting time which would increase admixture fluidity. Forty-five liters of $H_2O$, 567 L of Armak 4868 emulsion, and 0.9 t concrete sand were mixed for 10 min. Again during mixing, the admixture appeared as many laboratory 4868 admixtures, but upon reversing the drum direction for offloading, separation occurred which resulted in the water phase dumping followed by large lumps of admixture.

FIGURE 39. Transit Mixer Unloading Admix

### Other Spray-on Application Techniques

As discussed earlier, a rather large amount of 3-day- to 1-week-old +73 mV CMS-1 asphalt emulsion was available that could not be used in the other application machinery. In addition, a large radon source was located in the middle of the test plot possibly influencing after-seal radon flux measurements through overburden. Therefore, three other sprayed-on seals were applied to the test plot: hot rubberized asphalt, chip seal, and a fog seal.

#### Hot Rubberized Asphalt Seal[a]

Failure of the continuous portable pugmill to produce a radon seal material provided a small test strip for testing an additional application technique. Though not yet properly formulated as a radon seal, rubberized asphalt offers very low permeability in its applications as a moisture barrier. In Grand Junction, a small test strip of rubberized asphalt was applied to determine its effectiveness as a radon seal. The rubberized asphalt tested at Grand Junction consisted of asphalt combined with styrene-butadiene rubber to achieve a thermoplastic material with bulk properties like an elastomeric polymer. The rubber decreases the effect of temperature on asphalt viscosity after application, thus maintaining its high elastic properties. The rubberized asphalt is placed in two or more membrane layers or lifts over a prepared, smooth surface. Pinholes formed in the first lift from moisture escaping beneath the seal; the holes filled during subsequent passes. Typical application rates are 7 L/$m^2$ for a total membrane thickness of 5 to 8 mm.

Application of the rubberized asphalt membrane at the field test site went without difficulty. The material was applied through spray bars of a conventional distributor truck at 170$^{o}$C (see Figure 40). Because of its elastic qualities (1300% elongation) the mechanical strength of the membrane is not as critical as with asphalt emulsion admixtures. The effect of the rubberized asphalt on radon exhalation is discussed in a later section of this report.

#### Chip Seal

The concept, advantages, and disadvantages of a chip seal are described in the equipment screening section of this report. A chip spreader and crew

(a) The rubberized asphalt was supplied by Gilsabind Co., Mack, Colorado.

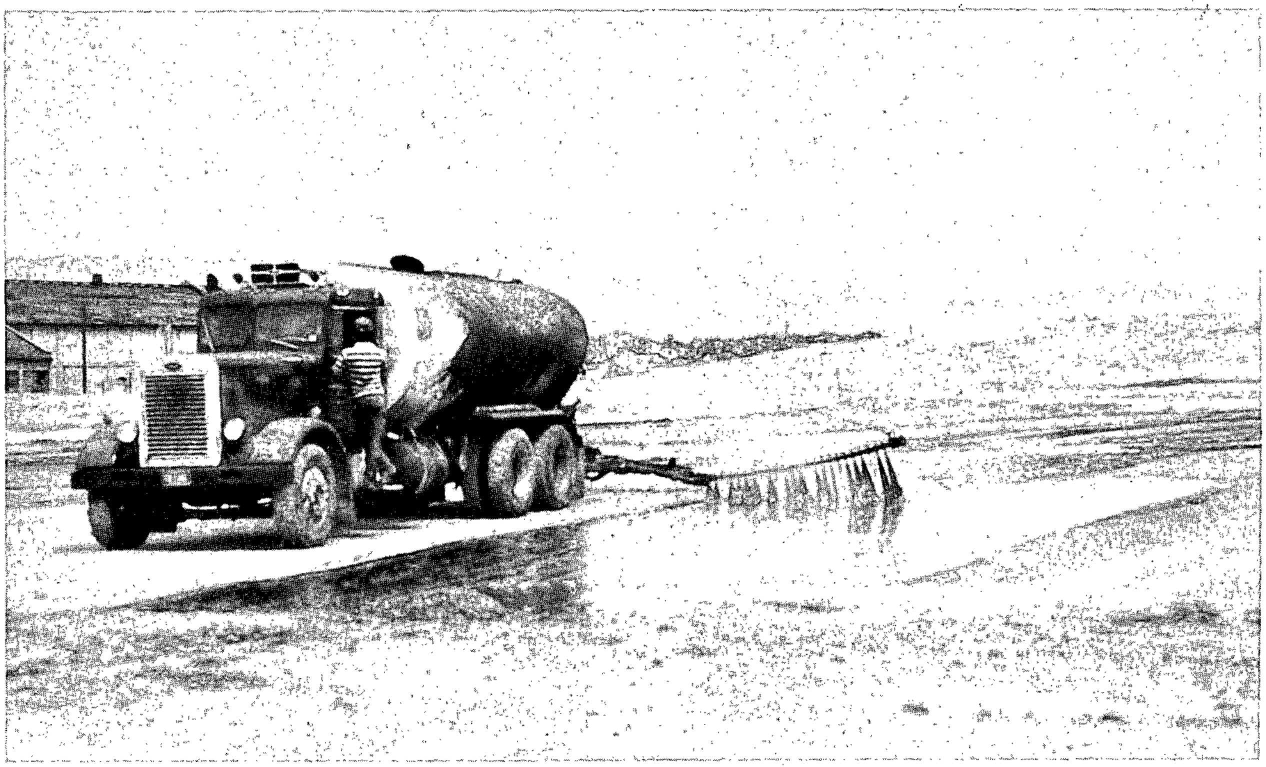

FIGURE 40. Application of Hot Rubberized Asphalt Seal

were generously donated by the city of Grand Junction, giving us the opportunity to field test the technique.

Actual application of a 1.3-cm (1/2-in.) seal involves five alternating steps: 1) light spray coating of asphalt emulsion, 2) immediate application of a 7-mm (1/4-in.) layer of concrete sand, 3) a heavy coat of asphalt emulsion, 4) another 7-mm (1/4-in.) layer of sand, and 5) application of a final layer of asphalt emulsion (see Figures 41 and 42). It is crucial to minimize runoff while obtaining the proper residual asphalt content. Approximately 3320 L (880 gal) of asphalt emulsion was required to obtain 22 residual wt% asphalt. This was divided evenly between the three coats to help minimize runoff.

Unfortunately, the pump on the distributor truck at maximum setting gave very inconsistent pumping rates. The first and second passes did not apply sufficient asphalt emulsion to the concrete sand; heavy runoff was already occurring. On the final pass, the distributor truck pump surprisingly applied almost twice as much asphalt emulsion as needed, increasing the amount of runoff.

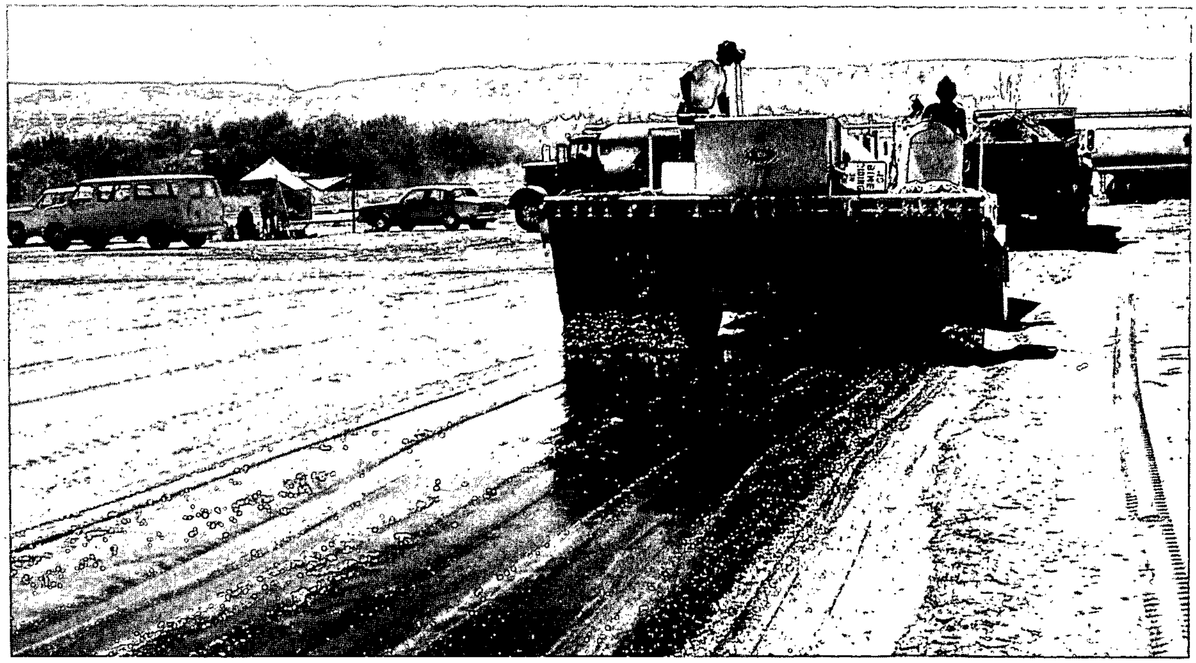

FIGURE 41. Chip Spreader Applying Layer of Sand Over Initial Coat of Asphalt Emulsion

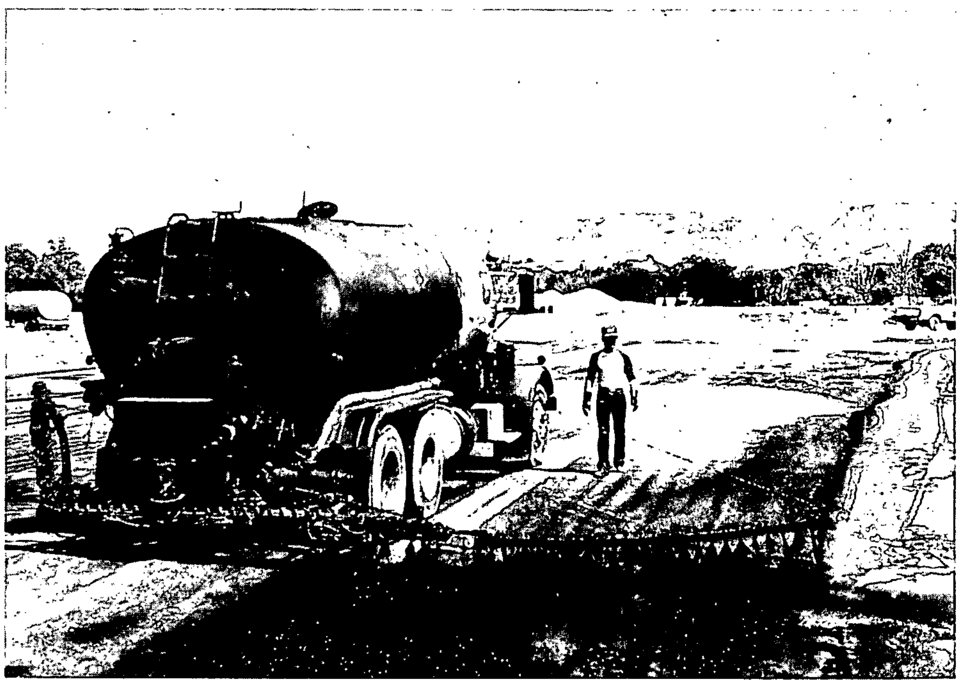

FIGURE 42. Distributor Truck Applying Final Layer of Asphalt Emulsion on Chip Seal

Control on such an operation is difficult, resulting in a seal of inconsistent structure. The unsatisfactory coating also obtained by poor penetration of asphalt emulsion into the thin layer of concrete sand resulted in an unwanted layered construction. While data are not sufficient for final conclusions yet, we are doubtful that this 3.6-m x 76-m (12-ft x 250-ft) seal using only concrete sand as the aggregate would survive severe freeze-thaw or other hostile environmental situations. If a macadam seal were prepared using a layering approach with the larger aggregate on the bottom working up to a finer aggregate at the top, the seal may be technically and economically feasible.

Fog Seal

The sealing concept of a fog seal was tested last year; its strengths and weaknesses are discussed in the 1979 Annual Report (Hartley et al. 1980). The fog seal was applied to the remaining test area to reduce interference from a large radon source within the test plot on initial after-seal radon measurements on overburden.

Reclamation

Reclamation of the asphalt emulsion radon barrier includes maintaining the protective cover over the admix seal. This involves revegetating the soil cover to prevent wind and water erosion. In addition, a biological barrier may be needed to prevent root and animal intrusion of the admix seal.

Overburden is the final layer of the integrated radon sealing system. In addition to protecting the asphalt from ultraviolet degradation, increasing depths of overburden correspondingly lower the oxygen content and thus lower the oxidation potential of the asphalt seal-atmosphere interface. At sufficient depths, overburden also reduces the strain of possible freeze-thaw stresses. Overburden was thus applied in depths of 20 to 122 cm (0.67 to 4 ft) on the test site. The overburden was also revegetated with selected natural and induced species in order to reduce wind and water erosion.

The roots of certain common plant species may cause possible damage to the asphalt seal. Certain burrowing animals pose another threat to the radon sealing system's integrity. To determine the possible effects of these environmental considerations, the DOE UMTRAP office is sponsoring studies conducted by PNL (Application of Long-Term Chemical Biobarriers for Uranium Mill Tailings) to examine the need for biological barriers such as herbicides, animal intrusion barriers, and revegetation. The southwest portion of the cold-mix paver seal was used for their field studies. Integrated sealing systems incorporating herbicides to inhibit root growth and rock layers to inhibit burrowing animals were constructed with long-term effects in mind.

## FIELD RADON MEASUREMENTS

To evaluate the effectiveness of the various sealing procedures, radon flux measurements must be made before and after seal application. A radon flux measurement system was designed and used in the 1979 field tudies (Hartley et al. 1980). The system used activated carbon at a dry ice-alcohol temperature (-78$^{o}$C) which the 1979 field studies demonstrated was inconvenient. The dry ice and alcohol were not easily obtained, stored, or handled in the field. In addition, use of the systems in remote locations, such as Shiprock, New Mexico, would greatly intensify the processing, storing, and handling problems. Therefore, a study was initiated to develop an improved radon flux measurement system. Once this system was developed, it was calibrated in the laboratory and used in the 1980 Grand Junction field test.

### Radon Measurement System Development

The study to develop an improved radon flux measurement system focused on determining the radon collection efficiency of activated carbon at higher temperatures. The apparatus used in this study (see Figure 43) consisted of a radon source, temperature bath, the activated carbon trap being tested, and a second activated carbon trap at -78$^{o}$C. Any radon that was not captured by the activated carbon in the first trap was captured by the second trap which is virtually 100% efficient at -78$^{o}$C. All tests ran for 4 h, a reasonable sampling time in the field.

The objective of the first set of tests was to determine the differences in radon collection efficiencies of various types of activated carbon on the market. The activated carbon types tested are listed as follows.

| Carbon | Description |
|---|---|
| Type 1 | PCC 8-12 mesh activated carbon |
| Type 2 | Non-impregnated carbon |
| Type 3 | PCC 10-20 mesh activated carbon |
| Type 4 | TEDA-impregnated carbon |
| Type 5 | Non-impregnated carbon |

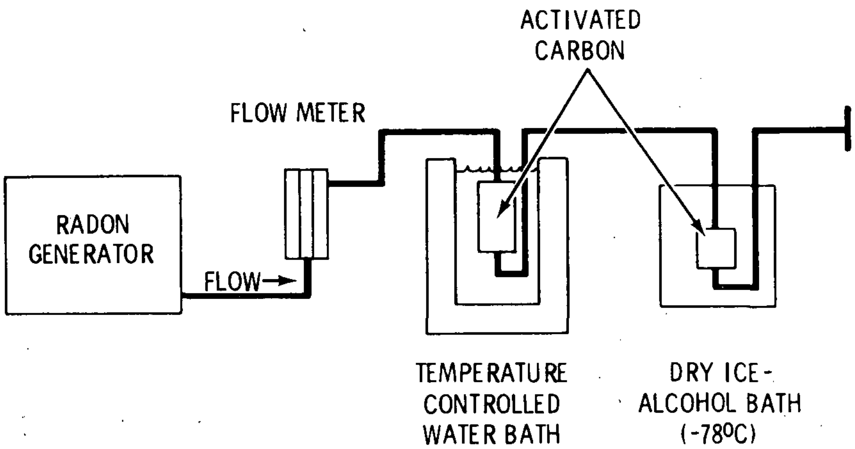


FIGURE 43. Apparatus Used to Determine Effectiveness of Carbon for Collecting Radon

The PCC carbon was the most efficient one tested as can be seen in Figure 44. The small particle size was slightly superior to the larger size. However, since the smaller particle size carbon was not readily available, the 8-12 mesh carbon was chosen for the remaining tests.

The next parameter that was investigated was bed configuration. Configurations tested included: a No. 1 tin can (6.8 cm dia x 10.2 cm) which holds 135 g of carbon, two No. 1 cans in tandem (270 g carbon total), a 3.3-cm-dia x 56-mm-long aluminum tube (200 g carbon), a 3.3-cm-dia x 56-cm-long aluminum tube with O rings spaced 2.54 cm apart on the inside (200 g carbon), and a 48-cm-dia x 61-cm-long convoluted steel tube (400 g carbon). Results of the tests are summarized in Figure 45.

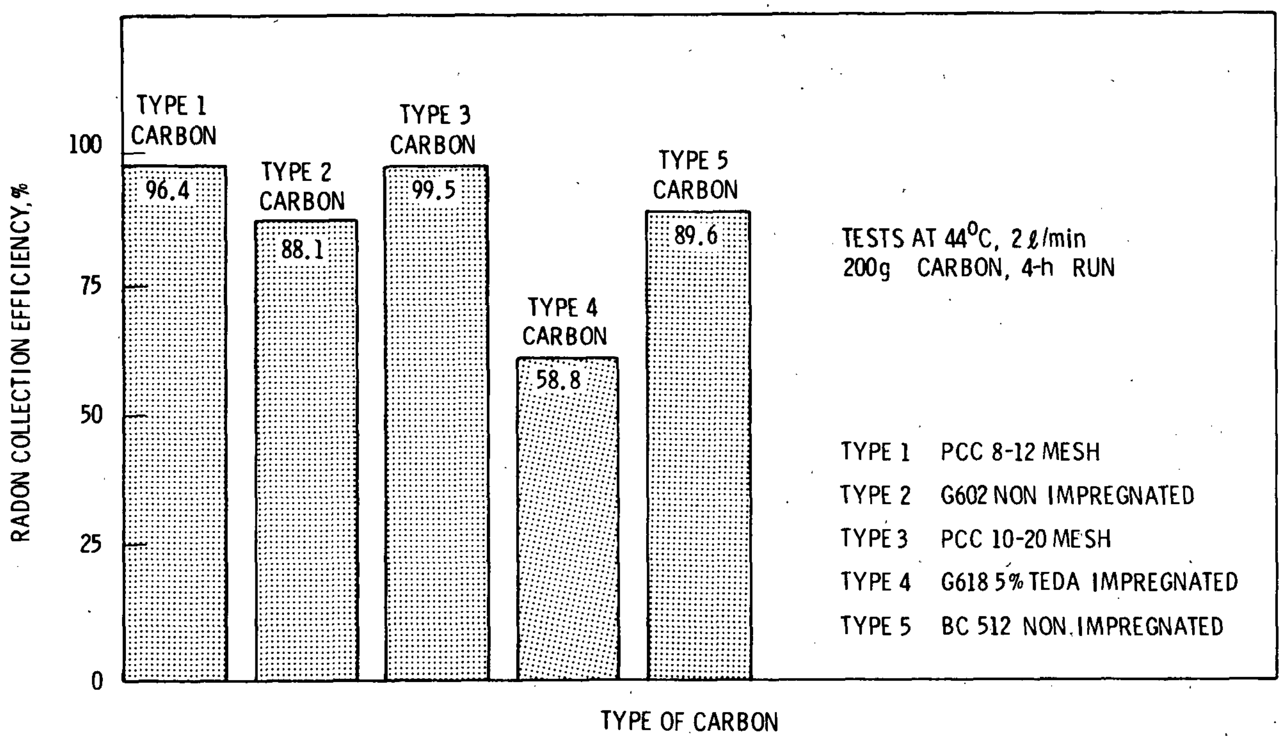


FIGURE 44. Effects of Carbon Type on Radon Collection Efficiency

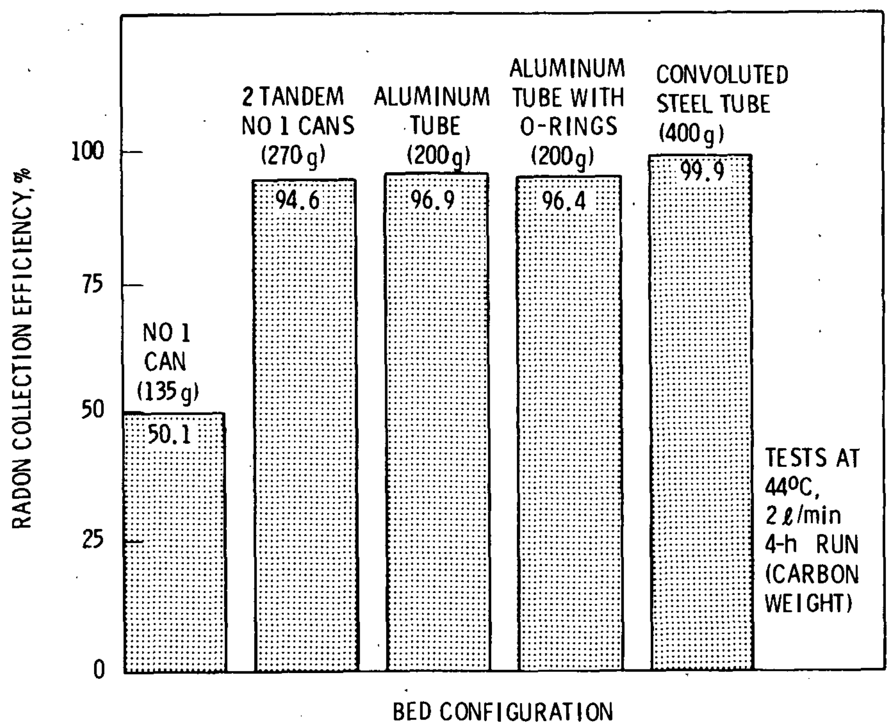


FIGURE 45. Effect of Bed Configuration on Radon Collection Efficiency

The convoluted steel tube was the most efficient bed configuration tested. This is due mostly to the larger carbon capacity than the other bed configurations. Also, the convoluted tube helps break up edge effects that might cause short circuiting of the radon through the carbon bed.

The final, and most important parameters investigated were flow rate and temperature. In order to keep the velocity and, therefore, the radon transport in the carbon bed at a minimum, flow rates of 2 and 4 L/min were chosen. The temperatures investigated ($0^{o}C$ to $60^{o}C$) included those that possibly would be encountered during field measurements. The results of the study are shown in Figure 46. Figure 46 shows that at temperatures up to $30^{o}C$ the efficiencies at both flowrates are the same. However, above $30^{o}C$ the efficiency at 4 L/min sharply decreases. Since temperatures above $30^{o}C$ were expected, 2 L/min was chosen as the flow rate to use in the field radon measurement system.

The field measurement system is a pressure-balanced recirculating system open to the atmosphere. A schematic diagram and picture of the system are shown in Figures 47 and 48. The system consists of a 77-cm x 122-cm x 5-cm

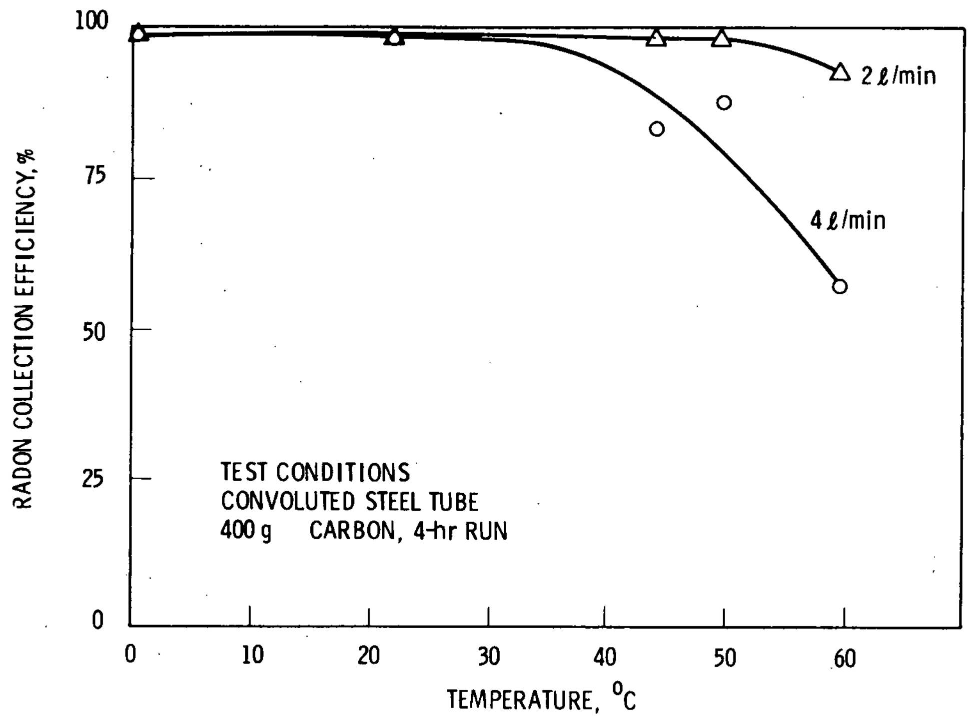


FIGURE 46. Effects of Temperature and Flow Rate on Radon Collection Efficiency

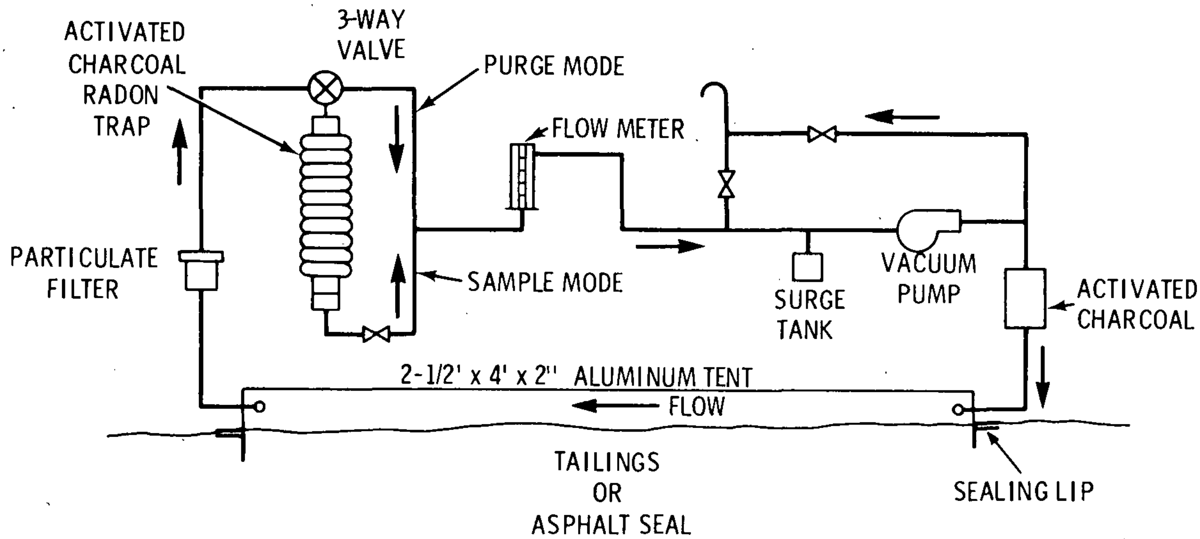


FIGURE 47. Radon Flux Field Measurement System

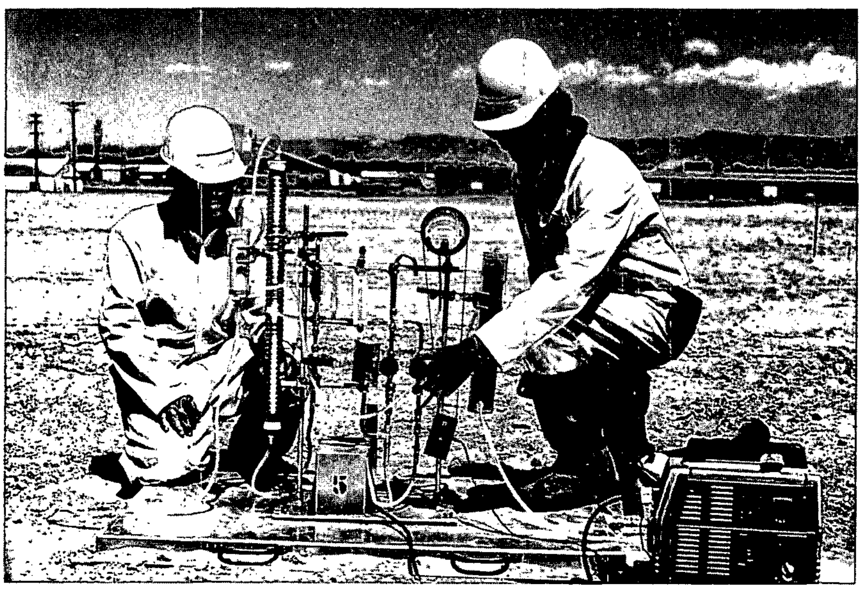

FIGURE 48. Field Radon Measurement System

aluminum tent placed on the area to be measured, a particulate filter to remove any small particles of tailings in the air flow, a radon trap to collect all the radon in the air flow, a flowmeter to regulate flow, a surge tank to dampen the pulsing action of the diaphram pump, the diaphram vacuum pump to provide the air flow, and an activated charcoal clean-up column to remove radon during purging.

The air flows across the tailings or asphalt seal where it picks up any radon exhaling from the measured area. The air then flows through a radon trap where all of the radon is collected on activated carbon which is later counted to determine the amount of radon collected.

The field radon measurements consist of the following steps.

- The tent is placed on the predetermined test spot and sealed to the tailings by pushing the lip into the tailings or by sealing the flange to the asphalt seal with caulking compound.
- The tent is purged with clean air for 15 min (2 volume changes) to remove any radon initially trapped under the tent during installation.
- The flow rate is adjusted to 2 L/min and the radon flux measurement is taken for 4 h from the time the flow starts through the activated charcoal radon trap.
- After the measurement is taken, the activated charcoal is placed in 2.5-cm- x 15.2-cm-dia plastic Petri dishes and subsequently counted using an intrinsic germanium diode counting system.

A more detailed procedure is presented in Appendix D.

A total of nine radon measurement tents were used to measure the radon flux. The tents were calibrated in the laboratory before they were used in the field. The laboratory calibration procedure consisted of placing the tent in a tub filled with sand and tailings as shown in Figure 49. Each tent was placed in the same spot over the tailings and radon exhalation measurements were taken for 4 h, using the same procedure that was used in the field. The radon flux measured by each of the tents was then compared. The flux measured by each of the tents was within $\pm 12\%$ of each other, demonstrating no significant differences in the measuring capabilities of the individual measurement systems. No attempt was made to calibrate the tents to measure absolute fluxes since no radon standard could be applied to our systems. Absolute fluxes were not needed since the systems were to be used for comparisons of relative before and after fluxes to determine seal effectiveness.

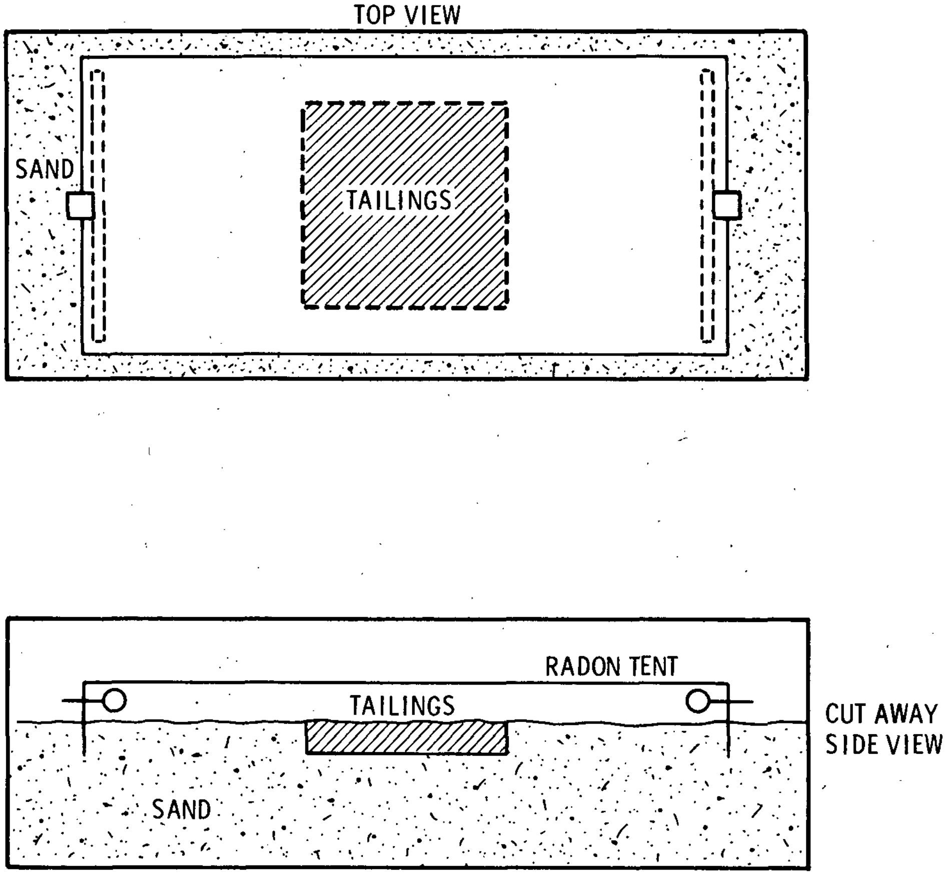


FIGURE 49. Tent Calibration Setup

The field counting system (see Figure 50) was calibrated by using two sources of Grand Junction tailings sealed in Petri dishes in epoxy. The standards were counted for $Bi^{214}$ peak periodically in the PNL multidimensional NaI counting system to determine when equilibrium between the tailings and radon had been reached. These standards were then counted in the field to determine the efficiency of the intrinsic germanium diode. An average efficiency of 0.3057% was determined for the diode that was used.

## Field Measurement

The field radon measurements consist of measuring the radon flux from the test area in Grand Junction before and after each asphalt emulsion sealing system application. The radon flux from the 76.2-m x 76.2-m (250-ft x 250-ft)

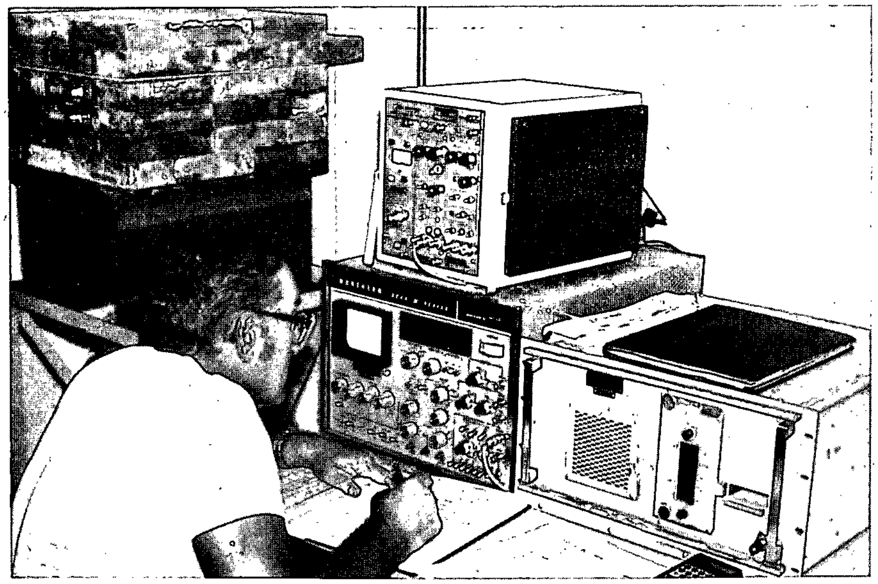

FIGURE 50. Field Counting System

asphalt emulsion test plot was measured on randomly located test points. The locations for each measurement were determined as follows.

- The asphalt emulsion system test area was divided into eighty 7.6-m x 9.8-m (25-ft x 32.3-ft) test areas.
- Random test point coordinates in each plot were determined using a random number generator program (Appendix D). (This method gives the advantages of random sampling while assuring the entire test area will be sufficiently sampled.)
- The test areas were then grouped into 19-m x 15.2-m (62.5-ft x 50-ft) test areas and the test points were labeled for future identification (see Figure 51).

These test points were used before and after the seals were applied to the tailings pile to ensure that before and after fluxes could be directly compared.

A total of 88 points was measured on tailings to determine the radon flux from the test area. The fluxes ranged from 86 to 1149 $pCi/m^2 \cdot s$ with an average

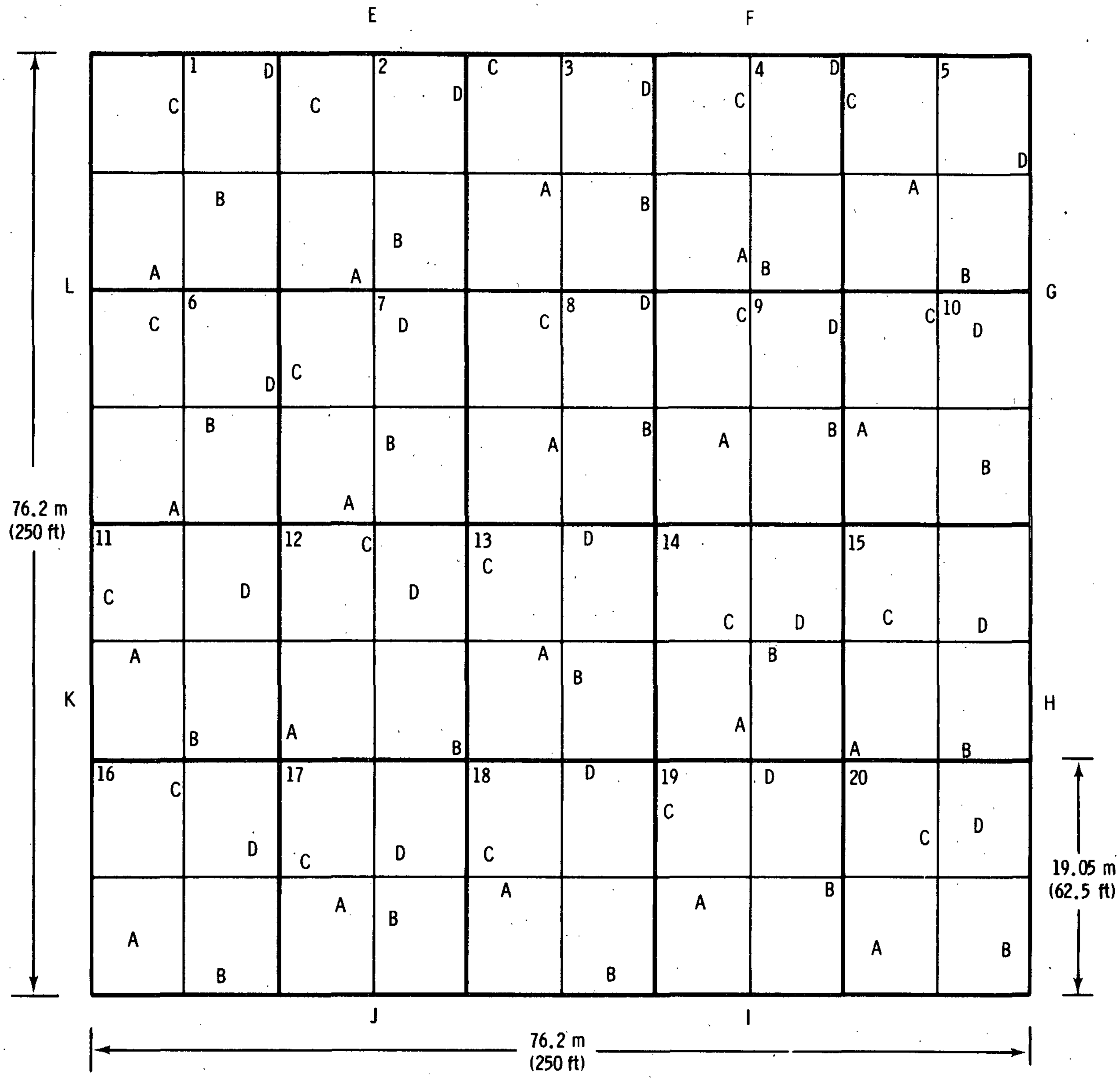


FIGURE 51. Radon Measurement Locations

and standard deviation of 410 and 343 $pCi/m^2 \cdot s$, respectively. The distribution of the radon fluxes is shown in Figure 52. The fluxes for each test point are shown in Figure 53.

Since the fluxes varied considerably throughout the test area, a geostatistical technique called Kriging was applied to the radon flux data.

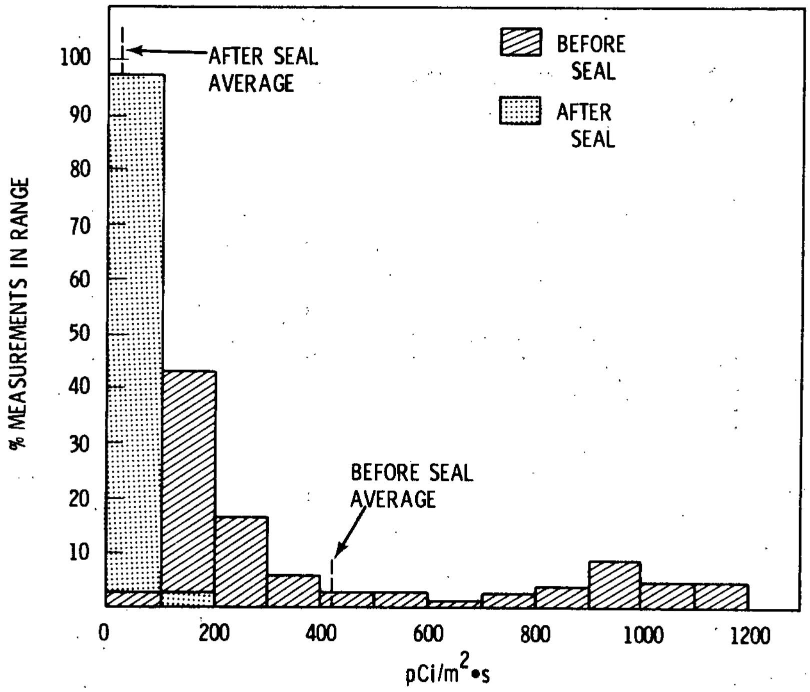


FIGURE 52. Distribution of Before and After Seal Radon Fluxes

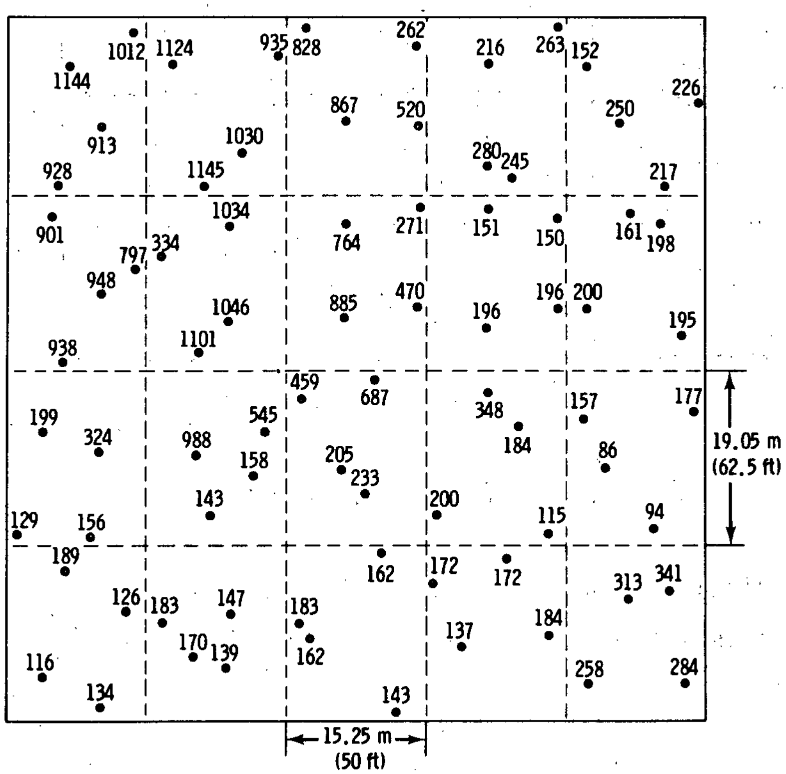


FIGURE 53. Radon Fluxes on Grand Junction Test Area

Basically, Kriging is a weighted moving-average technique that estimates the value of some spatial phenomenon at selected grid points using the data within the "neighborhood" around the grid point. This technique provides a "map" of the radon flux isopleths that can be used to predict the value of radon flux in an area that is not measured. The Kriging isopleth map for our test area is shown in Figure 54.

Twenty-five control measurements were taken on bare tailings at Grand Junction from August 8 to September 4 to determine the fluctuations in flux expected over a period of time from one area. The results of these measurements are shown in Figure 55. Fluxes ranged from 73 to 211 pCi/m$^2$•s. The average and standard deviations of the measurements were 111.0 $\pm$37.1 pCi/m$^2$•s.

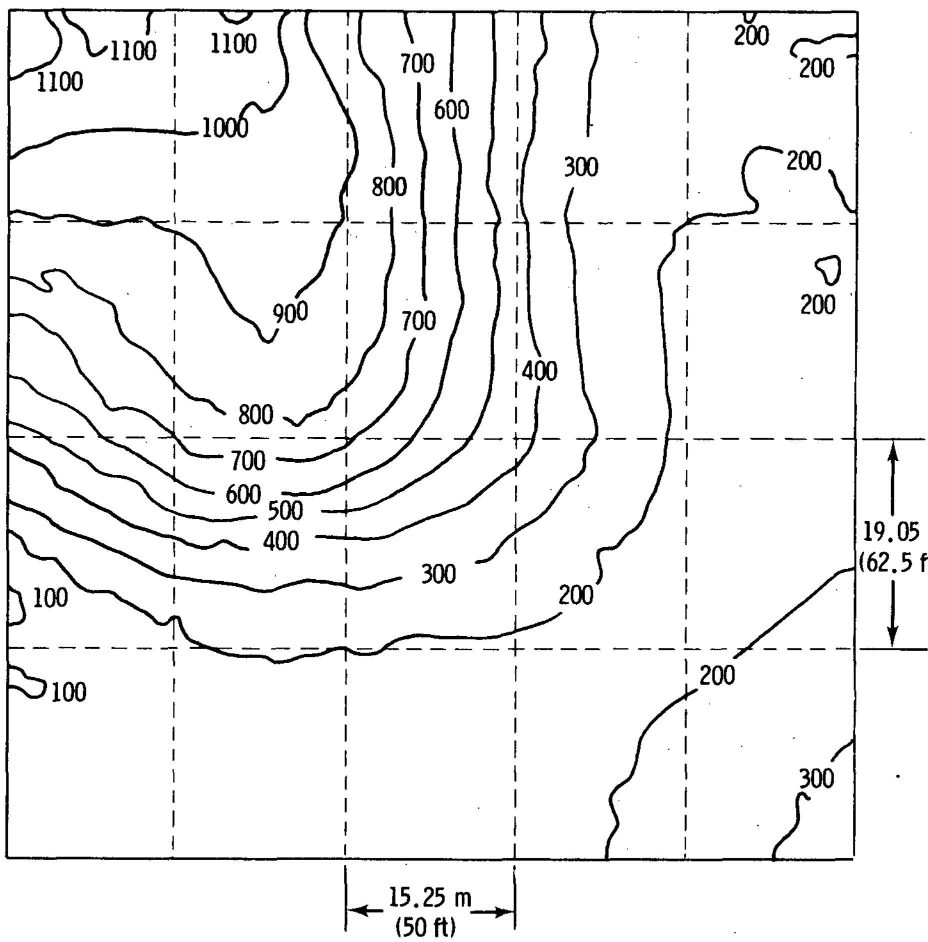


FIGURE 54. Kriging Radon Flux Isopleths

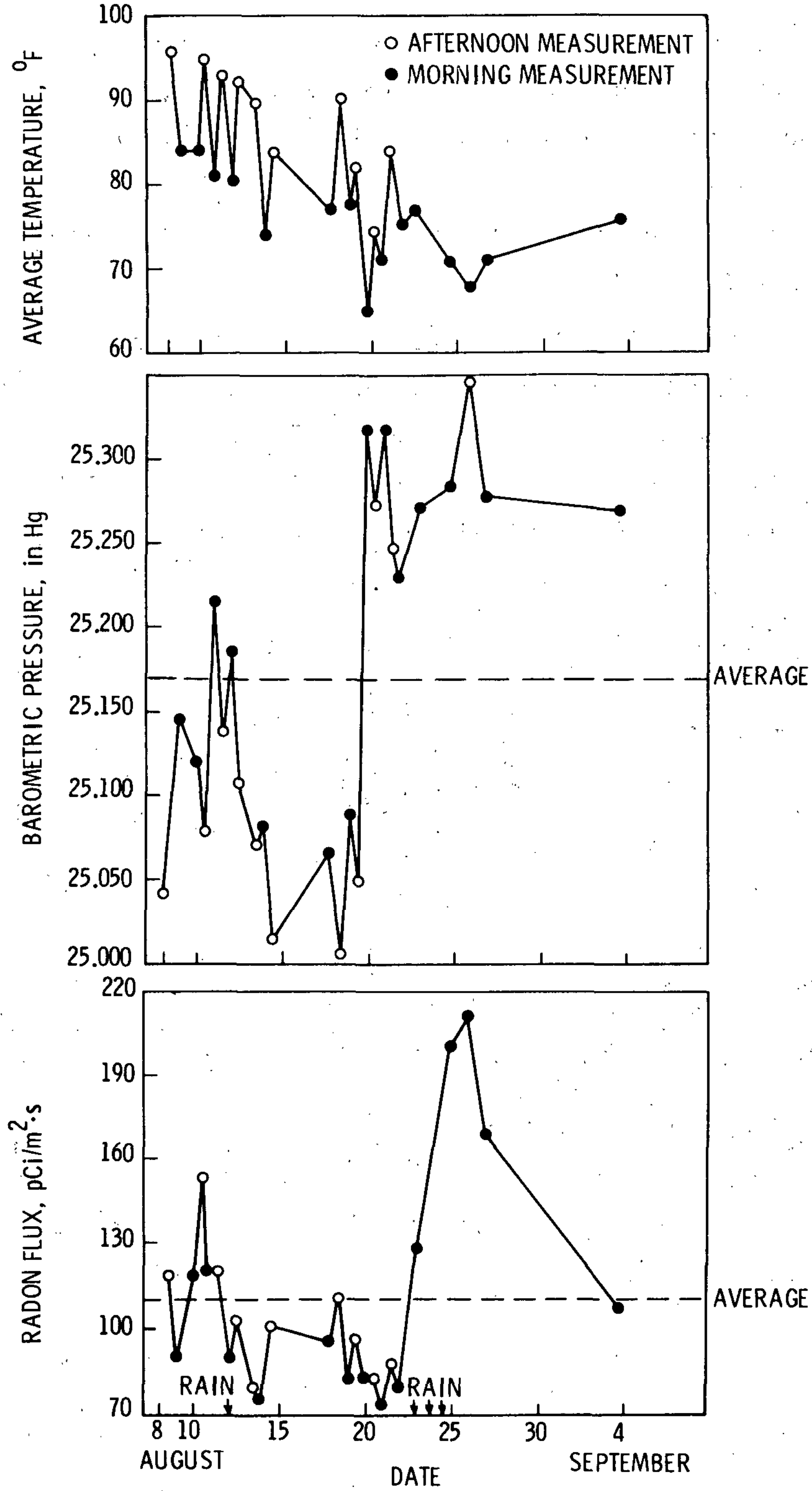


FIGURE 55. Control Radon Measurements and Meteorological Data

As shown in the figure, a fairly good correlation between barometric pressure and radon flux was observed. A decrease in barometric pressure generally resulted in an increase in radon flux and vice versa. An exception was observed on August 23 to 25 when an increase in barometric pressure was accompanied by a corresponding increase in radon flux. However, as noted in the figure, precipitation occurred during those three days. Since the radon measurement systems shielded the tailings from the moisture during those three days, the radon in the wet tailings surrounding the tent may have migrated to the porous dry area under the tent, resulting in higher measured radon fluxes.

Seventy-five radon measurements were made directly on the asphalt seal to determine seal effectiveness after the seals had been allowed to cure and undergo compaction. The measurements were taken using the same procedure as the before-seal measurements except that the lips were removed from the tents, and the tent was sealed to the asphalt by pressing the tent into the soft asphalt or by using caulking compound. The after-seal flux measurements varied according to the seal application technique that was used. A summary of the flux ranges and the flux reductions for each sealing technique is shown in Table 15. The fluxes for each point are shown in Figure 56. Table 15 reveals that the cold-mix paver was by far the most successful technique. In all cases the flux was reduced to 0.6 pCi/m$^2$·s or less.

The flux through the seal may not have been in equilibrium at the time of the first set of measurements. Therefore, we went back to the Grand Junction tailings pile during November 1980 to make additional radon flux measurements at selected locations on the test area. At this time overburden depths ranging from 0.3 to 1.2 m had been placed over the seal. The radon measurements were

TABLE 15. After-Seal Radon Fluxes in Each Test Area

| Application Technique | Flux Range pCi/m$^2$·s | Average Percent Flux Reduction |
|---|---|---|
| Soil Stabilizer | 0.6 - 178 | 96.5 |
| Cold Mix Paver | 0 - 0.6 | 99.9 |
| Chip Seal | 1.4 - 4.3 | 99.6 |
| Fog Seal | 0.3 - 344 | 95.7 |
| Hot Rubberized Asphalt | 0.5 - 12.9 | 99.3 |

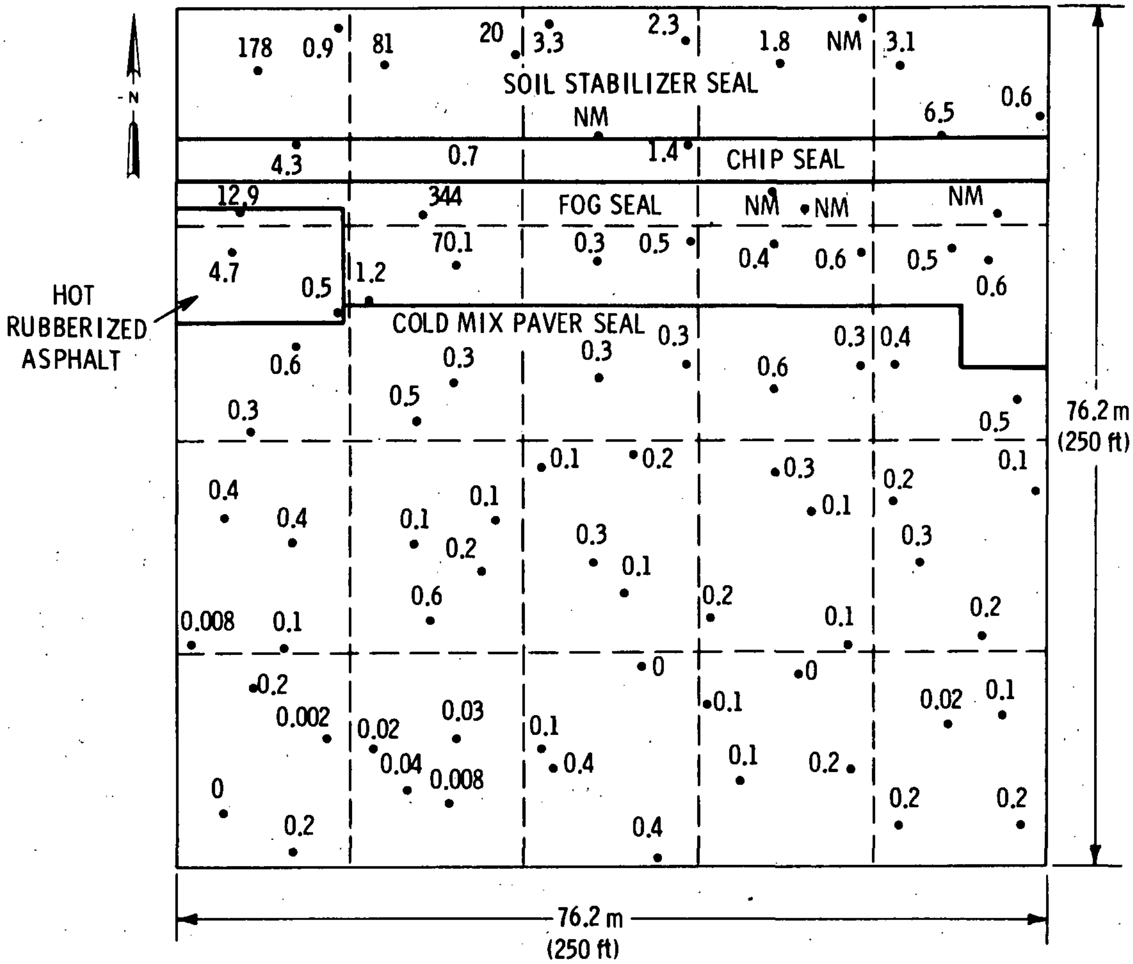


FIGURE 56. After-Seal Radon Fluxes

taken on the top of the overburden over the same locations that had been measured during the summer. The results of these measurements are shown in Figure 57. In most of the measurements taken during November, a slight increase in the radon flux was observed, indicating that the seal was not completely in equilibrium when the summer measurements were taken. However, the magnitude of the fluxes measured during November was still low (i.e., less than 2.0 $pCi/m^2 \cdot s$). Two exceptions are the two measurements taken on the edge of the seal area. Since there was 0.3 ft of overburden on top of the seal, the tents could not be sealed directly to the asphalt. Consequently, the radon could migrate around the edge of the seal into the overburden. To test this theory, we dug through the overburden on test plot 18B and measured the radon flux directly on the seal. With the direct measurement, the radon flux

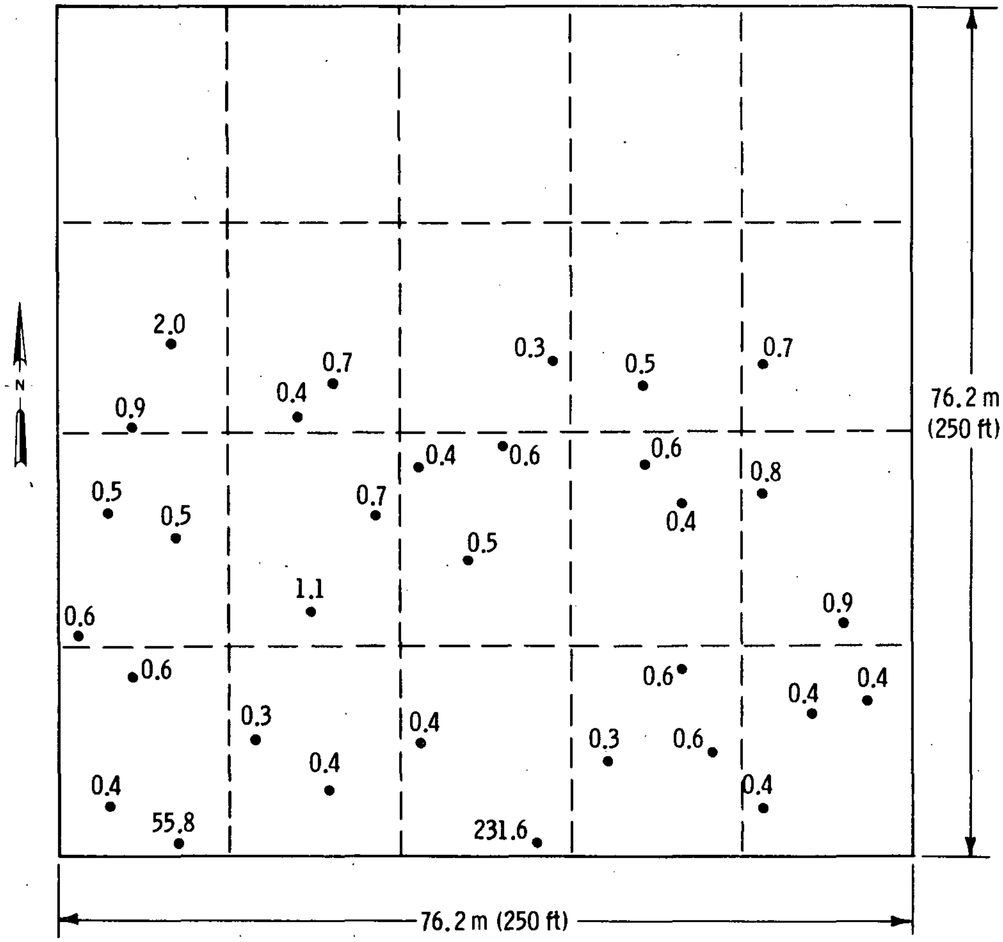


FIGURE 57. Fluxes from Grand Junction Tailings Pile During November 1980

decreased from 231.6 pCi/$m^2$·s to 1.4 pCi/$m^2$·s. This points out the necessity to ensure that future radon measurements be made far enough from the edge of the total seal to get away from this radon migration.

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# APPENDIX A

## LABORATORY TEST RESULTS

# TABLE A.1. Laboratory Test Results

| Test No. | Aggregate Type | Emulsion Type | wt% Asphalt | He Pressure Test | ΔP psi across seal | Test Duration, hours | % Flux Reduction | Comments |
|---|---|---|---|---|---|---|---|---|
| 1 | Grand Junction Tailings | Armak 4868 | 21.3 | passed | 0.3 | 23.5 | | Shipped to Prof. Markos, S. Dakota School of Mines |
| 2 | Grand Junction Tailings | Armak 4868 | 21.3 | passed | 0.3 | 23.5 | | Shipped to Prof. Markos, S. Dakota School of Mines |
| 3 | Tuba City-2 Tailings | Armak 4868 | 20 | passed | 0.3 | 94.5 | 98.26 | |
| 4 | Tuba City-2 Tailings | Armak 4868 | 20 | passed | 0.3 | 94.5 | 88.4 | post-test He check-leak |
| 5 | Shiprock-2 Tailings | Armak 4868 | 20 | passed | 0.3 | 48 | 99.97 | |
| 6 | Shiprock-2 Tailings | Armak 4868 | 20 | passed | 0.3 | 48 | 99.95 | |
| 7 | Shiprock-1 Tailings | Armak 4868 | 16.3 | passed | 0.3 | 72 | 61.8 | |
| 8 | Shiprock-1 Tailings | Armak 4868 | 22.3 | passed | 0.3 | 72 | 99.97 | |
| 9 | Shiprock-3 Tailings | Armak 4868 | 15 | passed | 0.3 | 71 | 98.8 | post He check-leak |
| 10 | Shiprock-3 Tailings | Armak 4868 | 20 | passed | 0.3 | 71 | 99.97 | |
| 11 | Shiprock-4 Tailings | Armak 4868 | 15 | passed | 0.3 | 72 | 96.86 | post He check-leak |
| 12 | Shiprock-4 Tailings | Armak 4868 | 20 | passed | 0.3 | 72 | 99.97 | |
| 13 | Tuba City-1 Tailings | Armak 4868 | 20 | passed | 0.3 | 0.3 | | seal failed under pressure |
| 14 | Tuba City-1 Tailings | Armak 4868 | 22.5 | passed | 0.3 | 72 | 99.25 | |
| 15 | Tuba City-3 Tailings | Armak 4868 | 20 | passed | 0.3 | 121.5 | 99.38 | |
| 16 | Tuba City-3 Tailings | Armak 4868 | 22.5 | passed | 0.3 | 121.5 | 99.72 | |
| 17 | Tuba City-4 Tailings | Armak 4868 | 20 | | | | | Formed clay balls coated with asphalt, not tested |
| 18 | Tuba City-4 Tailings | Armak 4868 | 22.5 | | | | | Formed clay balls coated with asphalt, not tested |
| 19 | Grand Junction Tailings | Armak 4868 | 15 | passed | 0.3 | 288 | 99.98 | |
| 20 | Grand Junction Tailings | Armak 4868 | 8.5 | failed | | | | |
| 21 | Hanford Blow Sand | Armak 4868 | 16.1 | passed | 0.3 | 144.5 | | |
| 22 | New Rifle-1 Tailings | Armak 4868 | 27.75 | failed | | | | Specimens contained considerable uncovered clay particles |
| 23 | New Rifle-1 Tailings | Armak 4868 | 36.6 | failed | | | | Specimens contained considerable uncovered clay particles |
| 24 | New Rifle-5 Tailings | Armak 4868 | 32.5 | failed | | | | Specimens contained considerable uncovered clay particles |
| 25 | Local Concrete Sand | Armak 4868 | 15 | failed | | | | |
| 26 | Local Concrete Sand | Armak 4868 | 18 | passed | | | | not tested |
| 27 | Local Concrete Sand | Armak 4868 | 18 | passed | 0.3 | 145.5 | 99.94 | |
| 28 | Local Sand G.J. Dist. | Armak 4868 | 19.7 | passed | 0.3 | 145.5 | | post He check-leak |
| 29 | -10 Hanford Blow Sand | Armak 4868 | 19.7 | passed | 0.3 | 49.3 | 99.98 | |
| 30 | Local Sand G.J. Dist. | Armak 4868 | 22.4 | passed | 0.3 | 49.3 | 99.98 | |
| 31 | 3/8 minus crushed rock | Armak 4868 | 15 | passed | 0.3 | 92 | 99.97 | |
| 32 | 3/8 minus crushed rock | Armak 4868 | 15 | failed | | | | |
| 33 | 3/8 minus crushed rock | Armak 4868 | 12 | failed | | | | |
| 34 | 3/8 minus crushed rock | Chevron 79R 3416 | 10 | failed | | | | |
| 35 | 3/8 minus crushed rock minimal fines | Armak 4868 | 12 | failed | | | | |
| 36 | 3/8 minus crushed rock minimal fines | Armak 4868 | 12 | failed | | | | |
| 37 | 3/8 minus crushed rock | Armak 4868 | 15 | passed | 0.3 | 92 | | |
| 38 | Local Sand G.J. Dist. | Chevron 79R 3416 | 10 | | | | | specimen fell apart |
| 39 | G.J. Tailings -28+200 | Armak 4868 | 18 | passed | 0.05 | 385 | 99.93 | |
| 40 | G.J. Tailings -28+200 | Armak 4868 | 18 | passed | 0.05 | 385 | 99.93 | |
| 41 | -10 Hanford Blow Sand | Chevron 79R 3416 | 18 | failed | | | | |
| 42 | -10 Hanford Blow Sand | Chevron 79R 3416 | 18 | failed | | | | |
| 43 | Local Sand G.J. Dist. | Armak 4868 | 22.4 | passed | | | | not tested |
| 44 | -10 Hanford Blow Sand | Armak 4868 Treflan Equiv. to 1.5 lb/acre | 19.7 | passed | 0.3 | 72 | 99.96 | |

## TABLE A.1. contd

| Test No. | Aggregate Type | Emulsion Type | wt% Asphalt | He Pressure Test | ΔP psi across seal | Test Duration, hours | % Flux Reduction | Comments |
|---|---|---|---|---|---|---|---|---|
| 45 | -10 Hanford Blow Sand | Armak 4868 Treflan Equiv. to 10 lb/acre | 19.7 | passed | 0.3 | 72 | 99.99 | |
| 46 | -10 Hanford Blow Sand | Armak 4868 Treflan Equiv. to 40 lb/acre | 19.7 | passed | 0.3 | 73 | 99.29 | |
| 47 | -10 Hanford Blow Sand | Armak 4868 | 19.7 | passed | 0.3 | 73 | 99.97 | |
| 48 | -10 Hanford Blow Sand | Chevron QS-h | 18 | passed | | | | not tested |
| 49 | -10 Hanford Blow Sand | Armak 4868 | 18 | failed | | | | |
| 50 | United Concrete Sand | Chevron CSS-1 | 15 | failed | | | | |
| 51 | United Concrete Sand | Chevron CSS-1 | 15 | failed | | | | |
| 52 | -10 Hanford Blow Sand | Chevron CSS-1 | 15 | passed | 0.3 | 90.7 | | |
| 53 | -10 Hanford Blow Sand | Chevron-QS-K-h | 18 | passed | | | | not tested |
| 54 | United Concrete Sand | Armak 4868 #1 | 20.5 | | | | | specimen cracked |
| 55 | United Concrete Sand | Armak 4868 #2 | 20.5 | passed | 0.3 | 120 | 98.90 | |
| 56 | United Concrete Sand | Armak 4868 #3 | 20.5 | passed | 0.3 | 74.5 | 99.99 | |
| 57 | United Concrete Sand | Armak 4868 #4 | 20.5 | passed | 0.3 | 74.5 | 99.99 | |
| 58 | United Concrete Sand | Armak 4868 #1 | 20.5 | failed | | | | |
| 59 | United Concrete Sand slope rolled | Armak 4868 #5 | 18 | passed | 0.3 | 72 | 99.97 | |
| 60 | Specimen from Colfax flat rolled | Union 76 CMS | 18.6 | passed | 0.3 | 70 | 99.99 | |
| 61 | Specimen from Colfax slope compacted | Union 76 CMS | 18.6 | passed | 0.3 | 70 | 99.99 | |
| 62 | Specimen from Colfax | Union 76 CMS | 18.6 | passed | 0.3 | 72 | 99.99 | |
| 63 | Specimen from Valley Slurry Seal Test | Chevron CQS | 22.2 | passed | 0.3 | 120 | 95.1 | |
| 64 | United Concrete Sand | Armak 56 mV | 20 | | | | | 15-s mix, not tested |
| 65 | United Concrete Sand | Armak 56 mV | 20 | | | | | 20-s mix, not tested |
| 66 | United Concrete Sand | Armak 56 mV | 20 | | | | | 10-min mix, foamed, not tested |
| 67 | United Concrete Sand | Armak 78 mV | 20.1 | passed | 0.3 | 95 | | |
| 68 | United Concrete Sand | U.S. Oil CMS-2 | 20.1 | | | | | specimen slumped badly |
| 69 | United Concrete Sand | Armak 56 mV | 20 | | | | | 30-s mix, not tested |
| 70 | United Concrete Sand | Armak 78 mV | 20.1 | | | | | 30-s mix, not tested |
| 71 | United Concrete Sand at 100°F | Armak 78 mV at 120°F | 20.1 | | | | | 30-s mix, not tested |
| 72 | United Concrete Sand at 100°F | Armak 56 mV at 130°F | 20.1 | | | | | 30-s mix, not tested |
| 73 | United Concrete Sand at 100°F | Armak 78 mV at 120°F | 20 | | | | | 30-s mix, not tested |
| 74 | United Concrete Sand | Armak 56 mV at 120°F | 20 | | | | | 30-s mix, not tested |
| 75 | United Concrete Sand | Armak 56 mV at 120°F | 20 | | | | | 6-min mix, not tested, foamed considerably |
| 76 | United Concrete Sand at 100°F | Chevron CMS-2 at 125°F | 20.1 | | | | | 30-s mix, not tested, slumped badly |
| 77 | Whitewater Sand at 100°F | Chevron CMS-2 at 125°F | 20.1 | | | | | 30-s mix, not tested, slumped badly |

## TABLE A.1. contd

| Test No. | Aggregate Type | Emulsion Type | wt% Asphalt | He Pressure Test | ΔP psi across seal | Test Duration, hours | % Flux Reduction | Comments |
|---|---|---|---|---|---|---|---|---|
| 78 | Whitewater Sand at 100°F | Chevron CMS-2 at 125°F | 17.3 | | | | | 30-s mix, not tested, slumped |
| 79 | Whitewater Sand at 100°F | Armak 56 mV | 20.1 | | | | | 25-min mix added tributylphosphate, n-octylalconol, still foamed |
| 80 | Whitewater Sand at 100°F | Armak 56 mV at 125°F | 20 | | | | | 30-s mix, not tested |
| 81 | Whitewater Sand at 100°F | Armak 56 mV at 125°F | 20 | | | | | 30-s mix, not tested |
| 82 | Whitewater Sand at 100°F | 50-50 Armak 56 & 78 at 125°F | 20 | | | | | failed, specimen appeared excellent |
| 83 | Whitewater Sand at 100°F | Armak 56 mV at 125°F | 20 | | | | | 15-s mix, not tested |
| 84 | Whitewater Sand | Armak 54 mV at 120°F | 20 | | | | | 30-min mixing, much less foaming than 56 mV |
| 85 | Whitewater Sand | Armak 62 mV at 120°F | 20 | | | | | 30-min mixing, not much foaming |
| 86 | Whitewater Sand | Armak 93 mV at 120°F | 20 | | | | | 15-s mix, set up immediately |
| 87 | Local Concrete Sand | Armak 54 mV at 125°F | 20 | | | | | 30-s mix, specimen slumped |
| 88 | Local Concrete Sand | Armak 62 mV at 125°F | 20 | | | | | 30-s mix, specimen slumped |
| 89 | Local Concrete Sand | Armak 93 mV at 125°F | 20 | | | | | 15-s mix, specimen rigid |
| 90 | Local Concrete Sand | Armak 62 m at 125°F | 20 | | | | | 30-s mix, specimen rigid |
| 91 | Local Concrete Sand | Armak 54 mV | 20 | | | | | 30-s mix, specimen rigid |
| 92 | Local Concrete Sand | Armak 56 mV | 19 | | | | | 30-s mix, specimen slumped |
| 93 | Local Concrete Sand | Armak 62 mV at 125°F | 20 | | | | | 30-s mix, specimen slumped after 2 weeks |
| 94 | Local Concrete Sand | Armak 78 mV at 125°F | 20 | | | | | 30-s mix, specimen slumped after 2 weeks |
| 95 | Local Concrete Sand | Armak 93 mV at 125°F | 20 | | | | | 30-s mix, specimen rigid |
| 96 | Local Concrete Sand | Armak 4868 #1 | 20.5 | | | | | 30-s mix, liquid-sand separation severe, discarded |
| 97 | Local Concrete Sand | Armak 4868 #2 | 20.5 | | | | | 30-s mix, liquid-sand separation, discarded |
| 98 | Local Concrete Sand | Armak 4868 #3 | 20.5 | | | | | 30-s mix, liquid-sand separation, discarded |
| 99 | Local Concrete Sand | Armak 4868 #4 | 20.5 | | | | | 30-s mix, liquid-sand separation, discarded |
| 100 | Local Concrete Sand | Armak 4868 #5 | 20.5 | | | | | 30-s mix, liquid-sand separation, discarded |
| 101 | Local Concrete Sand | Armak 4868 | 20.5 | | | | | 30-s mix, 3-step emulsion addition, liquid-sand separation, discarded |
| 102 | Local Concrete Sand | Armak 4868 #2 | 20.5 | | | | | 60-s mix, 3-step emulsion addition, liquid-sand separation, discarded |
| 103 | Local Concrete Sand | Armak 4868 #3 | 20.5 | | | | | 60-s mix, 3-step emulsion addition, liquid-sand separation, discarded |
| 104 | Local Concrete Sand | Armak 4868 #4 | 20.5 | | | | | 60-s mix, 3-step emulsion addition, liquid-sand separation, discarded |
| 105 | Local Concrete Sand | Armak 4868 #5 | 20.5 | | | | | 60-s mix, 3-step emulsion addition, liquid-sand separation, discarded |
| 106 | Local Concrete Sand | Armak 56 mV | 18.4 | | | | | 60-s mix, 3-step emulsion addition excellent |
| 107 | Local Concrete Sand | Armak 4868 #1 | 17.6 | | | | | 30-s mix, specimen had obvious voids, discarded |
| 108 | Local Concrete Sand | Armak 4868 #2 | 17.6 | | | | | 30-s mix, specimen fell apart |

## TABLE A.1. contd

| Test No. | Aggregate Type | Emulsion Type | wt% Asphalt | He Pressure Test | ΔP psi across seal | Test Duration, hours | % Flux Reduction | Comments |
|---|---|---|---|---|---|---|---|---|
| 109 | Local Concrete Sand | Armak 4868 #3 | 17.6 | | | | | 30-s mix, specimen appears to have voids |
| 110 | Local Concrete Sand | Armak 4868 #4 | 17.6 | | | | | 30-s mix, not tested |
| 111 | Local Concrete Sand | Armak 4868 #5 | 17.6 | | | | | 30-s mix, not tested |
| 112 | Local Concrete Sand | Armak 56 mV | 18.0 | passed | 0.3 | 49 | | |
| 113 | Local Concrete Sand | Armak 56 mV | 18.0 | passed | 0.3 | 49 | | |
| 114 | Local Concrete Sand | Armak 4868 #1 at 90°F | 18.5 | | | | | not tested, specimen appears good |
| 115 | Local Concrete Sand | Armak 4868 #1 at 90°F | 20.1 | | | | | not tested, specimen appears good |
| 116 | Local Concrete Sand | Armak 4868 #2 at 90°F | 18.5 | | | | | not tested, specimen appears good |
| 117 | Local Concrete Sand | Armak 4868 #2 at 90°F | 20.1 | | | | | not tested, specimen excellent |
| 118 | Local Concrete Sand | Armak 4868 #3 at 90°F | 18.5 | | | | | passed specimen good |
| 119 | Local Concrete Sand | Armak 4868 #3 at 90°F | 20.1 | | | | | not tested, specimen excellent |
| 120 | Local Concrete Sand | Armak 4868 #4 at 90°F | 18.5 | | | | | not tested, specimen good |
| 121 | Local Concrete Sand | Armak 4868 at 90°F | 20.1 | | | | | not tested, specimen excellent |
| 122 | Local Concrete Sand | Armak 4868 #5 at 90°F | 18.5 | | | | | not tested, good specimen |
| 123 | Local Concrete Sand | Armak 4868 #5 at 90°F | 20.1 | | | | | not tested, excellent specimen |
| 124 | Local Concrete Sand | Armak 56 mV | 18 | | | | | 30-s mix specimen contained excess water |
| 125 | Local Concrete Sand | Armak 54 mV | 18 | | | | | 30-s mix, less foaming than 56 mV |
| 126 | Local Concrete Sand | Armak 62 mV | 18 | | | | | 30-s mix, excellent specimen |
| 127 | Local Concrete Sand | Armak 78 mV | 18.2 | | | | | 30-s mix, good specimen |
| 128 | Local Concrete Sand | Armak 56 mV | 18.1 | | | | | 30-s mix, excellent specimen |
| 129 | -10 Hanford Blow Sand | Armak 4868 #2 at 110°F | 18.2 | | | | | 30-s mix, pressed at 100°F, excellent specimen |
| 130 | -10 Hanford Blow Sand | Armak 4868 #3 at 110°F | 18.2 | | | | | 30-s mix, pressed at 108°F, excellent specimen |
| 131 | -10 Hanford Blow Sand at 110°F | Armak 4868 #4 at 110°F | 18.2 | | | | | 30-s mix, pressed at 100°F, good specimen |
| 132 | -10 Hanford Blow Sand at 110°F | Armak 4868 #5 at 110°F | 18.2 | | | | | 30-s mix, pressed at 100°F, good specimen |
| 133 | -10 Hanford Blow Sand | Armak 78 mV | 18.0 | | | | | 30-s mix, pressed while at room temperature, porous specimen |
| 134 | -10 Hanford Blow Sand | Armak 4868 #2 | 18.2 | | | | | 30-s mix, pressed at 90°F, excellent specimen |
| 135 | -10 Hanford Blow Sand | Armak 4868 #3 | 18.2 | | | | | 30-s mix, pressed at 90°F, excellent specimen |
| 136 | -10 Hanford Blow Sand | Armak 4868 #4 | 18.2 | | | | | 30-s mix, pressed at 90°F, excellent specimen |
| 137 | -10 Hanford Blow Sand | Armak 4868 #5 | 18.2 | | | | | 30-s mix, pressed at 90°F, excellent specimen |
| 138 | | | | | | | | |
| 139 | United Concrete Sand | Armak 78 mV | 18.0 | | | | | Admixture pressed over G.J. tailings, treated with 5% Coherex |

# APPENDIX B

## LONG-TERM STABILITY RESEARCH PLAN

# LONG-TERM STABILITY RESEARCH PLAN

Very little research has been reported about the long-term stability of asphalt liners, i.e., irrigation systems, aqueducts, or chemical waste storage systems. Our literature search indicated that no accelerated stability test procedures are applicable to buried asphalt liners. The accelerated tests that are available were developed for asphalt pavement. Consequently, they depend upon high-intensity ultraviolet light and/or high temperatures for rapid asphalt degradation. As long as the integrity of the overburden is maintained, the asphalt admix should not be exposed to such conditions.

The lack of a meaningful accelerated stability test limits an immediate determination of the longevity of the asphalt radon barrier. However, the combination of laboratory and field studies should allow longevity of the system to be ascertained within a 2- to 5-year period. The length of this period is due to the necessity of monitoring the asphalt admix in the field. These observations would help confirm the laboratory results, in particular, rate studies.

The literature search and experimental work to date indicated that oxidation, aqueous leaching, microbial attack, and temperature cycling are probably the most likely mechanisms of degradation to be encountered by asphalt radon barriers. The individual and collective contributions of these potential mechanisms are presented in Figure B.1. These mechanisms and respective laboratory or field tests are discussed below.

## OXIDATION

The oxidative degradation of asphalt encompasses three processes: photo-oxidation, thermal oxidation and catalytic oxidation. Microbial attack is also an oxidative process; however, discussion of that route of asphalt degradation will be dealt with in a separate section.

Photo-oxidation (light-catalyzed oxidation) need not be considered during this research since the asphalt barrier is covered with about 1 m of overburden. Thermal oxidation will be considered an oxidative process which, although

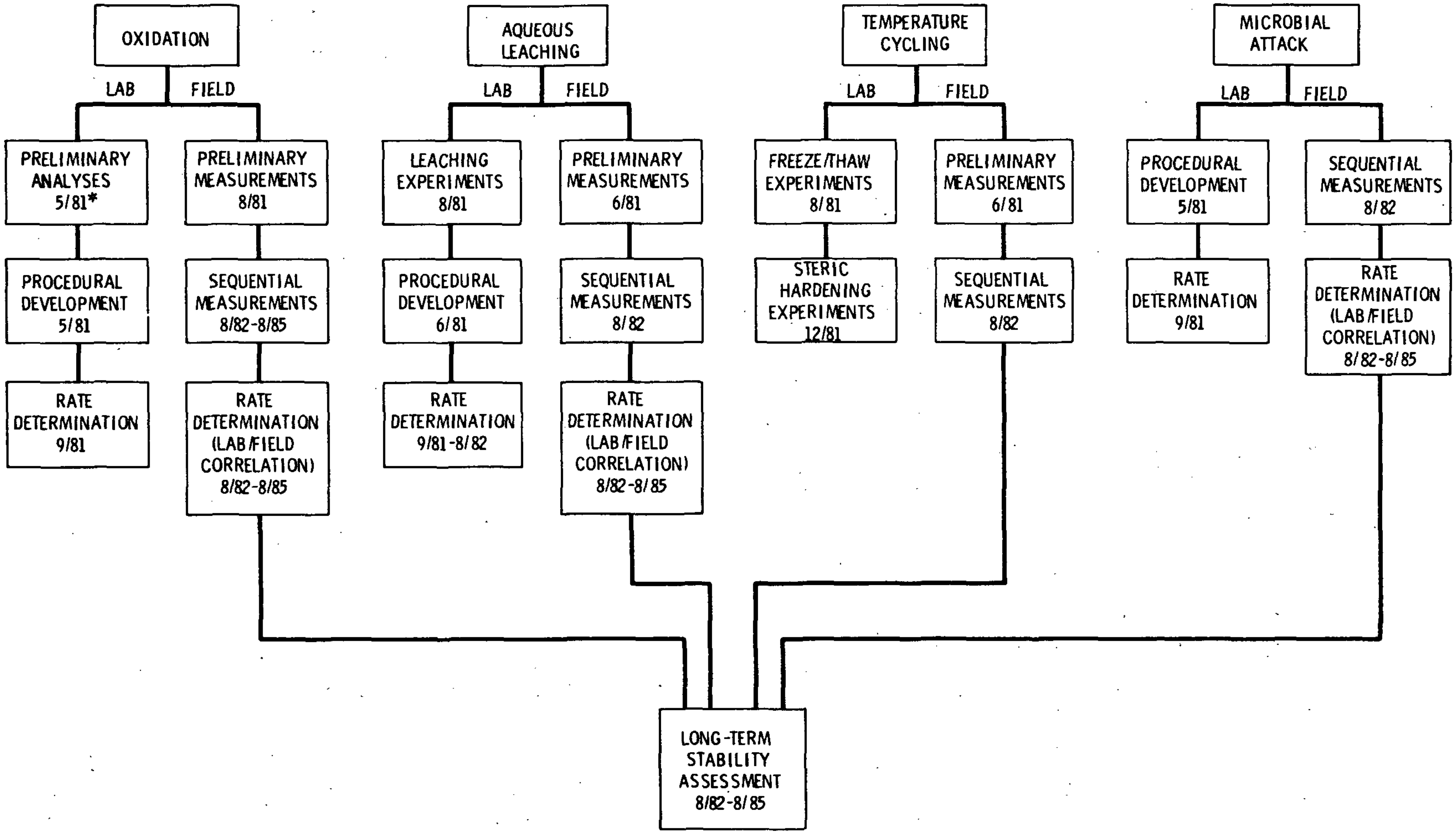



FIGURE B.1. Potential Mechanisms for Degradation of Asphalt Radon Barriers[a]

(a) The dates in the boxes indicate the anticipated completion of the respective tasks.

free radical in nature, is neither catalyzed by light nor metallic compounds. This process is obviously dependent upon the amount of oxygen available at the asphalt-overburden interface. Oxygen may be available to the interface in either a gaseous or dissolved state. Assuming a specific gravity of 1.5 for the overburden, the amount of dissolved oxygen available to the asphalt overburden interface should be about 0.5 ppm $cm^3$. This route of oxygen transport would not be a large contributing factor to asphalt oxidation. However, gaseous transport would not be so hindered. Measurements of gaseous oxygen in the overburden particularly at the interface, will be determined both in the field and the laboratory by a polarographic technique (Patrick 1977). This would also help determine the rate of diffusion of the gaseous oxygen through the overburden.

Infrared spectroscopy (IR) will be used to determine the amount of oxidized material on/in asphalt samples of known age. Once this procedure has been established, field samples (covered by overburden) will be examined. The extent of oxidation can be determined by the IR procedure with microtomed layers of the asphalt. These layers would be sliced at specific depths parallel to the interface surface. This would allow us to estimate the rate of field oxidation.

Measurement of the oxidation rate is necessary in order to estimate the durability of the asphalt barrier. Two procedures will be examined in the laboratory. Both estimate the oxidation rate of asphalt by measuring the volume of oxygen consumed, assuming a direct relationship between the uptake of oxygen and oxidation. The first procedure, a manometric technique, was used previously to measure the oxygen consumption of asphalt films (Van Oort 1956; Blokker and Van Hoorn 1959). This procedure provided for the determination of the diffusion coefficient and the depth of penetration into the asphalt film. The overall rate of oxygen absorption is dependent upon the physical transport of oxygen as well as the chemical nature of the asphalt. The second procedure requires laser-Raman spectroscopy. Samples of asphalt in an oxygen atmosphere are sealed in glass ampoules. The oxygen content of ampoules can be directly measured by the laser-Raman instrument. Once a relative rate of oxidation is obtained in the laboratory, field studies will be initiated. The IR technique, discussed previously, should allow estimation of the oxygen involvement with asphalt. Aqueous leaching and microbial attack may contribute to asphalt surface attrition. Thus, several field samples must be examined.

In light, the presence of vanadium in asphalt has been shown to affect the rate at which asphalt degrades (Green, Tolonen and Peters 1976). This correlation of increased vanadium to increased oxidation was also noted in the dark using a rolling, thin-film oven test. Consequently, vanadium and other metals may provide a catalytic enhancement of oxidation. The cationic asphalt will be analyzed for vanadium, molybdenum and other metals. This will help determine if metallic catalysis has a role in the oxidation of the asphalt seals.

## AQUEOUS LEACHING

Aqueous leaching (surface dissolution) of asphalt may involve the asphalt-overburden interface and the asphalt-tailings interface. Thus, the potential for surface leaching must be investigated with both interfaces. Asphalt-overburden experiments will involve the circulation of distilled water over the asphalt emulsion admix seals for specific time periods (6 to 12 months). The leachate will be extracted and analyzed for degraded asphalt components. Admittedly, the use of distilled water will not simulate actual field conditions since it ignores the finite salt concentrations emanating from the overburden. However, it will provide a comparison to the leaching experiments which will simulate the aqueous exposure of the asphalt-tailings interface. Such a comparison could establish whether high-salt concentrations enhance dissolution of the asphalt interface. Thus, the asphalt-tailings leaching experiments will be conducted in a manner similar to that described above. However, the circulating solution will contain salts identified as present in the aqueous extract of Grand Junction tailings. If asphalt components are identified in the leachate, it may prove useful to microtome surface layers from the test seals to determine the depth of leaching involvement. This would provide an estimate of the leaching rate. The weight of the leached material could also confirm this rate. The amount of moisture available at both the asphalt-overburden and asphalt-tailings interfaces will be determined in the field by tensiometry over a 1- to 2-yr period. This will help establish whether or not aqueous leaching is an actual problem in the field. At the same time, field pH meter probes will be placed at the asphalt-tailings interface to determine acidity conditions. It should be noted that the average rainfall for this region is 8.5 in. The amount of rain per year is generally distributed equally except during the month of August when about 1 in. of rain falls from thundershowers. We surmise that the amount of water available to both interfaces is minimal. However, if the field measurements indicate otherwise, a more complete asphalt surface testing may be required. Such surfaces would be examined by scanning electron microscopy to determine if the asphalt was pitted or corroded. Both oxidation and microbial attack may contribute to the surface attrition.

## TEMPERATURE CYCLING

Building recommendations for the Grand Junction area call for 3-ft foundations. This indicates that the frontline may have the potential of reaching the asphalt interface through 1 m of overburden. Thus, the effect of freeze-thaw cycling upon the asphalt seal will be investigated. This may be determined with a water susceptibility test (Plancher et al. 1980). In this test, asphalt briquets of special design are submerged in water and subjected to repeated freeze-thaw cycling on a stress pedestal until the briquets crack. This test may require modification since it was originally developed for porous road asphalt.

Steric harderning (an increase of viscosity due to the loss of low molecular weight components or to a differential separation of components by molecular weight) should also be investigated. Microviscosimetry would be performed on samples of known age and known asphalt content. This procedure would also be applied to samples of the asphalt barrier. Oxidation and microbial attack may contribute to the segregation and hardening process.

It is not anticipated that the temperature will vary greatly at the asphalt-overburden interface. If, indeed, the interfacial temperature does not fluctuate greatly, the contribution of temperature cycling may not be measurable. Consequently, a soil temperature profile will be obtained from the Grand Junction site. In particular, the temperature at the asphalt-overburden interface will be established over a 1-to 2-yr period.

## MICROBIAL ATTACK

Microbial degradation of asphalt has been well recognized as a predominantly aerobic process (ZoBell and Molecke 1978), although anaerobic microbial oxidation has been observed (Traxler and Bernard 1969). Several genera of bacteria have been implicated as having the capacity to oxidize asphalt. During our research we have also noted the presence of fungal colonies on the surfaces of discarded asphalt seals that were used in leaching experiments. Thus, equipment and solutions in contact with asphalt must be sterilized prior to experimentation to eliminate microorganisms as an uncontrolled variable.

The comparison of various types of asphalt can be obtained by pulverizing seal samples and placing them in an innoculated nutrient medium. Each unit weight of microbial biomass (expressed as carbon) will indicate that at least a like amount has been removed from asphalt. This does not account for the loss of carbon dioxide from the complete oxidation. Thus, the evolution of carbon dioxide can provide a procedure for measuring microbial degradation of asphalt. Oxygen uptake is normally used as an indicator of the amount of oxidized carbon compound. However, the effect of the thermal oxidation of asphalt could provide deceptive information.

The rate of microbial degradation under normal conditions is usually quite slow; several months are usually required to obtain definitive results. Thus, an estimation of the rate of microbial oxidation of an intact seal surface may require 1 to 2 years under controlled conditions. The monitoring of cell growth and carbon dioxide production should provide a means for measuring asphalt degradation. It should be noted that these degradation experiments will not represent field conditions.

Asphalt-coated coupons of known weight will be placed at various depths in the field. Coupon samples will be examined at specific times to determine the microbial involvement of the asphalt surfaces as well as weight loss. Soil samples will also be obtained at various depths relative to the coupons and the asphalt barrier. The numbers (population size) of bacteria/fungi in relation to a depth profile would provide a crude procedure to correlate the field information to laboratory rate data.

# APPENDIX C

## GRAND JUNCTION COVER AND TAILINGS PHYSICAL CHARACTERIZATION

ARMSTRONG ENGINEERS and ASSOCIATES, INC.

861 Rood Avenue — Grand Junction, Colorado 81501 — (303) 245-3861

June 27, 1980

Battelle
Pacific Northwest Laboratories
P. O. Box 999
Richland, Washington 993532

Attn: David Esterl and
Jim Hartley

Re: Laboratory and Field Test Results
Job #802854

Gentlemen:

We have completed the lab and field testing outlined in Phase I of Battelle's purchase order #B-A5965-A-Q. The purpose of this letter is to explain the finalized results which are attached on separate pages.

We have summarized the results of the laboratory tests performed on the silty clay overburden (cover) soil, the maroon colored tailings sand and the tan colored tailings sand. These results are summarized on the first page attached to this letter. All laboratory testing was done in accordance with standard ASTM procedures. We feel that our summary is for the most part self-explanatory, however, our method of supplying the swell data should be explained. Our swell results were determined during the CBR tests. The samples were prepared and compacted in the CBR molds and then, as per ASTM guidelines, initial height of sample readings were recorded prior to soaking. Height of sample readings were again recorded after the sample soaked for a period of 96 hours. The swell values reported are the results of calculations based on these readings. It must be kept in mind by the user of these results that these swell values are equated using CBR apparatus with the soils initially at the density and moisture given in our summary of results.

The results of the sand cone density testing are tabulated starting on the second sheet attached. The locations of the tests as well as depths are also tabulated and a drawing showing the sample locations is provided following the results. Locations 1 through 9 are the center of the respective grids shown in the location drawing. Locations 10, 11, and 12 are shown in the drawing with an X and the respective location number. Please note that the depths recorded for these density tests are given for a 6 inch interval. This is because densities, by nature, are based on volume, and the volumes tested were approximately 6 inches deep. In other words, a hole of approximately 6 inches in depth was used for each sand cone test.

Nuclear density test results are not given, although quite a few tests were taken prior to abandoning this method. Results from our nuclear density gauge were good on the surface where gamma attenuation was greatest, however, they were poor below the tailings cover of clay.

Also attached you will find copies of our CBR graphs, modified proctor compaction graphs, sieve analysis graphs, and various data sheets pertaining to these graphs.

Should you have any questions concerning this data or this letter, please call.

Sincerely,

ARMSTRONG ENGINEERS AND ASSOCIATES, INC.

Byron W. Kelly

Byron W. Kelly
Geotechnical Engineer

Approved By:

Edward A. Armstrong

Edward A. Armstrong, PE-LS
President

BWK/kr

## SUMMARY OF RESULTS

Silty clay overburden (depth 0"-6")

LL = 38.5  PI = 17.3  Classification: CL
CBR = 2 at 96.6% optimum density (modified proctor)
Swell = 6.3% at 111.6 PCF dry density
Optimum dry density = 115.5 PCF
Optimum moisture = 15.1%

Marroon tailings (depth 6"-18")

LL = NP  PI = NP  Classification: SM or SC
CBR = 3 at 96.7% optimum density (modified proctor)
Swell = 0.1% at 105.2 PCF dry density
Optimum dry density = 108.7 PCF
Optimum moisture = 12.6%

Tan tailing (depth 6"-18")

LL = NP  PI = NP  Classification: sand
CBR = 12 at 96% optimum density (modified proctor)
Swell = 1.7% at 99.0 PCF dry density
Optimum dry density = 102.8 PCF
Optimum moisture = 10.8%

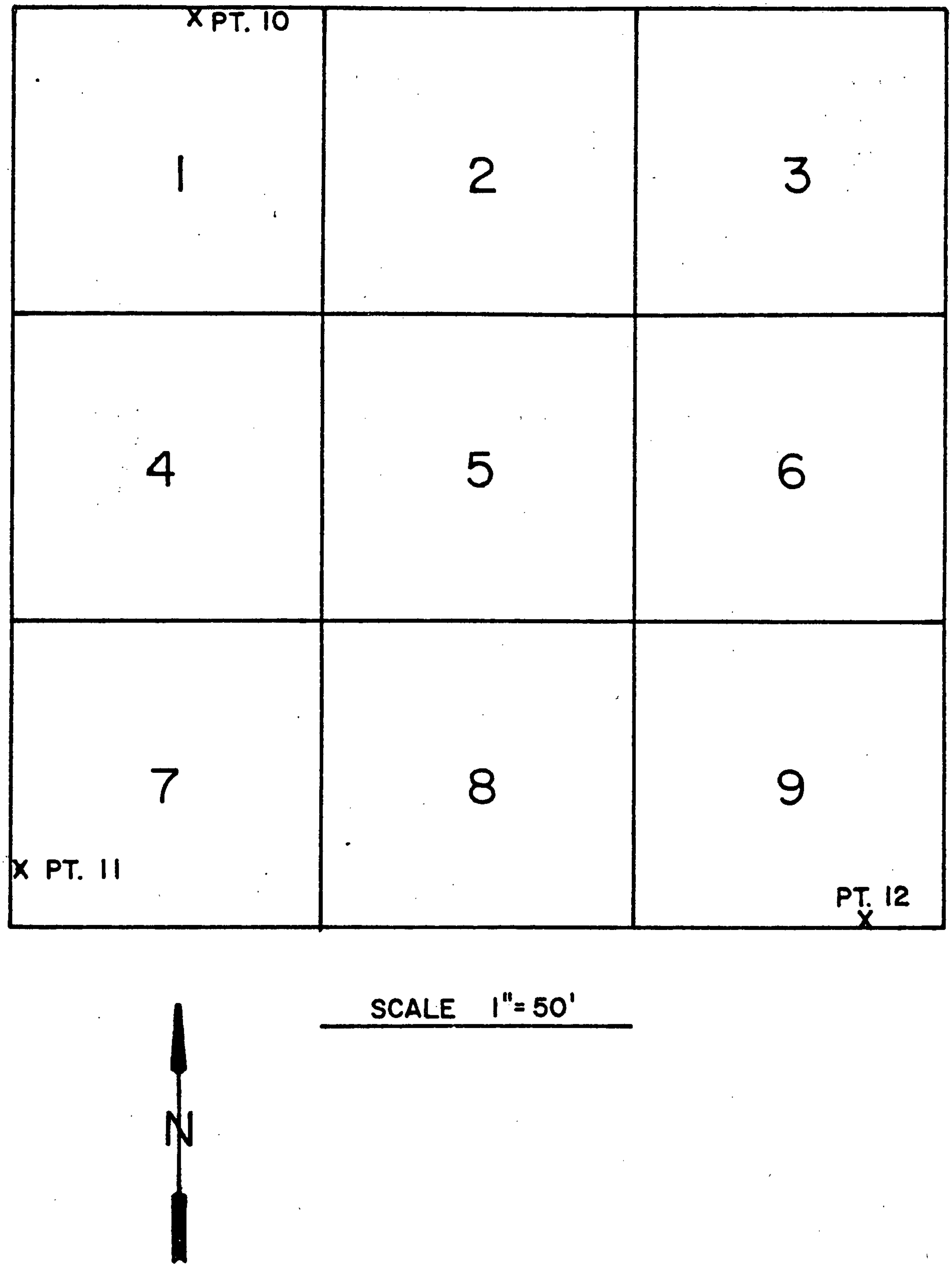
RESULTS OF SAND CONE DENSITY TESTS

| LOCATION | DEPTH (Inches) | DRY DENSITY | MOISTURE |
|---|---|---|---|
| 1 | 0-6 | 89.6 | 13.3 |
| | 6-12 | 94.3 | 9.6 |
| | 12-18 | 102.6 | 8.6 |
| | 18-24 | 100.2 | 10.2 |
| 2 | 0-6 | 82.6 | 8.9 |
| | 6-12 | 100.0 | 9.4 |
| | 12-18 | 98.5 | 4.8 |
| | 18-24 | 104.6 | 2.2 |
| 3 | 0-6 | 82.5 | 11.9 |
| | 6-12 | 97.9 | 3.4 |
| | 12-18 | 99.0 | 2.4 |
| | 18-24 | 95.2 | 2.9 |
| 4 | 0-6 | 84.2 | 10.5 |
| | 6-12 | 102.5 | 9.3 |
| | 12-18 | 102.3 | 9.6 |
| | 18-24 | 104.0 | 9.6 |
| 5 | 0-6 | 93.4 | 9.7 |
| | 6-12 | 102.0 | 12.5 |
| | 12-18 | 102.0 | 10.0 |
| | 18-24 | 93.8 | 14.6 |
| 6 | 0-6 | 86.5 | 7.5 |
| | 6-12 | 102.2 | 2.4 |
| | 12-18 | 103.0 | 2.4 |
| | 18-24 | 102.7 | 3.0 |
| 7 | 0-6 | 83.0 | 8.4 |
| | 6-12 | 94.6 | 2.3 |
| | 12-18 | 98.9 | 2.4 |
| | 18-24 | 101.1 | 2.4 |
| 8 | 0-6 | 85.0 | 9.8 |
| | 6-12 | 102.4 | 2.2 |
| | 12-18 | 104.7 | 2.5 |
| | 18-24 | 99.6 | 2.5 |
| 9 | 0-6 | 91.2 | 6.6 |
| | 6-12 | 104.9 | 2.8 |
| | 12-18 | 103.4 | 2.6 |
| | 18-24 | 102.8 | 2.1 |

Results of Sand Cone Density Tests
Page 2

| LOCATION | DEPTH (Inches) | DRY DENSITY | MOISTURE |
|---|---|---|---|
| 10 | 0-6 | 89.9 | 11.0 |
| | 6-12 | 104.2 | 7.2 |
| | 12-18 | 103.1 | 7.1 |
| | 18-24 | 95.2 | 5.3 |
| 11 | 0-6 | 88.4 | 9.9 |
| | 6-12 | 104.0 | 2.6 |
| | 12-18 | 101.1 | 2.7 |
| | 18-24 | 95.1 | 3.1 |
| 12 | 0-6 | 81.8 | 13.8 |
| | 6-12 | 77.7 | 20.6 |
| | 12-18 | 75.5 | 21.9 |
| | 18-24 | 70.2 | 23.4 |

LOCATION OF FIELD TESTING



APPENDIX D

# DETAILED FIELD RADON MEASUREMENT PROCEDURE

## DETAILED FIELD RADON MEASUREMENT PROCEDURE

(see Figure D.1)

1. Seal tent to tailings or asphalt seal.
2. Close valve 2 and turn valve 1 to B position.
3. Turn on vacuum pump.
4. Close valve 3 all the way. The tent is now in the purge mode. Purge tent for minimum of 15 minutes (~2 volume changes).
5. Hook up lines that go to ends of tent to T fitting attached to a Magnehelic.
6. Turn valve 1 to A position, valve 2 to on position.
7. Adjust flow rate to approximately 2 L/min.
8. Adjust valve 4 to get zero pressure differential. Reattach lines to tent ends.
9. Start timer. The system is now in the sample mode.
10. Sample for 4 hours.
11. Turn valve 2 to the off position.
12. Remove radon trap and plug ends with rubber stoppers.
13. Log date, time on, time off, accumulated time in Radon Measurement log book.

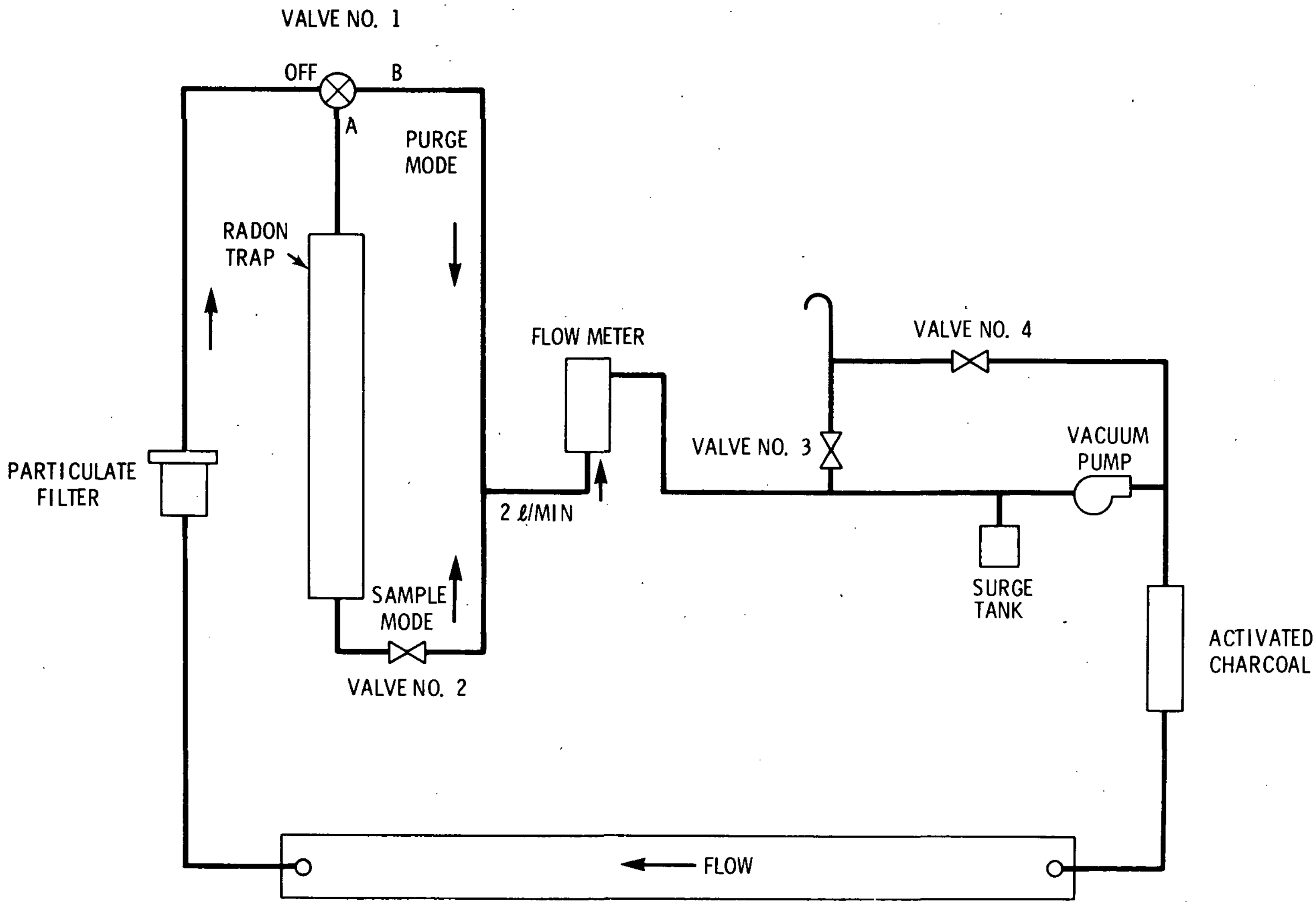



FIGURE D.1. Detailed Schematic of Radon Measurement System

TABLE D.1. Sample Site Location Coordinates Asphalt Emulsion System

| Area | Plot | X (ft) | Y (ft) |
|---|---|---|---|
| 1 | A | 16 | 5 |
| | B | 34 | 25 |
| | C | 23 | 48 |
| | D | 45 | 57 |
| 2 | A | 20 | 2 |
| | B | 34 | 15 |
| | C | 10 | 46 |
| | D | 46 | 50 |
| 3 | A | 22 | 26 |
| | B | 48 | 25 |
| | C | 7 | 60 |
| | D | 47 | 52 |
| 4 | A | 22 | 12 |
| | B | 30 | 8 |
| | C | 21 | 48 |
| | D | 48 | 61 |
| 5 | A | 18 | 30 |
| | B | 33 | 4 |
| | C | 7 | 49 |
| | D | 46 | 36 |
| 6 | A | 23 | 3 |
| | B | 33 | 25 |
| | C | 18 | 54 |
| | D | 46 | 39 |
| 7 | A | 17 | 7 |
| | B | 30 | 18 |
| | C | 4 | 42 |
| | D | 32 | 50 |
| 8 | A | 22 | 18 |
| | B | 48 | 23 |
| | C | 20 | 50 |
| | D | 48 | 61 |
| 9 | A | 18 | 17 |
| | B | 48 | 19 |
| | C | 22 | 59 |
| | D | 46 | 53 |
| 10 | A | 6 | 23 |
| | B | 39 | 13 |
| | C | 21 | 59 |
| | D | 33 | 54 |
| 11 | A | 13 | 29 |
| | B | 31 | 7 |
| | C | 5 | 46 |
| | D | 40 | 48 |
| 12 | A | 2 | 14 |
| | B | 33 | 6 |
| | C | 23 | 57 |
| | D | 35 | 44 |
| 13 | A | 19 | 28 |
| | B | 30 | 21 |
| | C | 6 | 53 |
| | D | 32 | 59 |
| 14 | A | 23 | 11 |
| | B | 38 | 25 |
| | C | 17 | 35 |
| | D | 40 | 39 |
| 15 | A | 4 | 5 |
| | B | 31 | 4 |
| | C | 14 | 42 |
| | D | 34 | 37 |
| 16 | A | 14 | 15 |
| | B | 35 | 5 |
| | C | 22 | 55 |
| | D | 40 | 39 |
| 17 | A | 15 | 24 |
| | B | 29 | 22 |
| | C | 7 | 35 |
| | D | 32 | 37 |
| 18 | A | 8 | 27 |
| | B | 40 | 2 |
| | C | 7 | 37 |
| | D | 33 | 61 |
| 19 | A | 12 | 23 |
| | B | 45 | 29 |
| | C | 4 | 50 |
| | D | 28 | 58 |
| 20 | A | 9 | 14 |
| | B | 42 | 24 |
| | C | 23 | 44 |
| | D | 36 | 45 |

TABLE D.2. Radon Flux Measurements and Meteorological Data From Grand Junction Field Test

| Sample Location | Flux, $pCi/m^2 \cdot S$ Before | Flux, $pCi/m^2 \cdot S$ After | Flux Reduction, % | Before Seal: Tailings Moisture, % | Before Seal: Relative Humidity, % | Before Seal: Temperature Average $^oC$ | Before Seal: Barometric Pressure in Hg |
|---|---|---|---|---|---|---|---|
| 1A | 928 | 12.9 | 98.61 | 3.31 | 18 | 28.5 | 25.040 |
| B | 913 | 4.3 | 99.53 | 1.37 | 18 | 28.5 | 25.040 |
| C | 1144 | 178.0 | 84.41 | 2.93 | 33 | 26.0 | 25.145 |
| D | 1012 | 0.9 | 99.91 | 5.34 | 33 | 26.0 | 25.145 |
| 2A | 1149 | 344.0 | 70.00 | 2.91 | 33 | 26.0 | 25.145 |
| B | 1030 | 0.7 | 99.93 | 2.38 | 33 | 26.0 | 25.145 |
| C | 1124 | 81.0 | 92.79 | 4.69 | 33 | 26.0 | 25.145 |
| D | 935 | 20 | 97.86 | 2.25 | 33 | 26.0 | 25.145 |
| 3A | 867 | -- | -- | 2.05 | 33 | 26.0 | 25.145 |
| B | 520 | 1.4 | 99.73 | 1.51 | 33 | 26.0 | 25.145 |
| C | 828 | 3.3 | 99.60 | 6.43 | 17 | 33.0 | 25.063 |
| D | 262 | 2.3 | 99.12 | 2.47 | 17 | 33.0 | 25.063 |
| 4A | 280 | -- | -- | 0.79 | 17 | 33.0 | 25.063 |
| B | 245 | -- | -- | 0.87 | 17 | 33.0 | 25.063 |
| C | 216 | 1.8 | 99.17 | 2.18 | 17 | 33.0 | 25.063 |
| D | 263 | -- | -- | 1.68 | 17 | 33.0 | 25.063 |
| 5A | 249 | 6.5 | 97.39 | 1.25 | 17 | 33.0 | 25.063 |
| B | 217 | -- | -- | 0.94 | 17 | 33.0 | 25.063 |
| C | 152 | 3.1 | 97.96 | 2.26 | 24 | 25.5 | 25.119 |
| D | 226 | 0.6 | 99.73 | 1.09 | 24 | 25.5 | 25.119 |
| 6A | 938 | 0.3 | 99.97 | 6.60 | 18 | 28.5 | 25.040 |
| B | 948 | 0.6 | 99.94 | 3.55 | 18 | 28.5 | 25.040 |
| C | 901 | 4.7 | 99.48 | 7.14 | 18 | 28.5 | 25.040 |
| D | 797 | 0.5 | 99.94 | 4.50 | 18 | 28.5 | 25.040 |
| 7A | 1101 | 0.5 | 99.95 | 6.22 | 27 | 27.0 | 25.136 |
| B | 1046 | 0.3 | 99.97 | 4.21 | 27 | 27.0 | 25.136 |
| C | 334 | 1.2 | 99.64 | 2.03 | 18 | 28.5 | 25.040 |
| D | 1034 | 70.1 | 93.22 | 1.37 | 18 | 28.5 | 25.040 |

TABLE D.2. contd

| Sample Location | Flux, pCi/m$^2$·S Before | Flux, pCi/m$^2$·S After | Flux Reduction, % | Before Seal: Tailings Moisture, % | Before Seal: Relative Humidity, % | Before Seal: Temperature Average $^0$C | Before Seal: Barometric Pressure in Hg |
|---|---|---|---|---|---|---|---|
| 8A | 885 | 0.3 | 99.97 | 1.88 | 27 | 27.0 | 25.136 |
| B | 470 | 0.3 | 99.94 | 2.70 | 27 | 27.0 | 25.136 |
| C | 764 | 0.3 | 99.96 | 1.30 | 27 | 27.0 | 25.136 |
| D | 271 | 0.5 | 99.81 | 2.06 | 27 | 27.0 | 25.136 |
| 9A | 196 | 0.6 | 99.69 | 2.01 | 16 | 28.0 | 25.094 |
| B | 196 | 0.3 | 99.85 | 2.75 | 16 | 28.0 | 25.094 |
| C | 151 | 0.4 | 99.74 | 2.15 | 27 | 27.0 | 25.136 |
| D | 150 | 0.6 | 99.60 | 1.08 | 27 | 27.0 | 25.136 |
| 10A | 200 | 0.4 | 99.80 | 2.43 | 16 | 28.0 | 25.094 |
| B | 161 | 0.5 | 99.69 | 2.19 | 16 | 28.0 | 25.094 |
| C | 161 | 0.5 | 99.69 | 1.74 | 16 | 28.0 | 25.094 |
| D | 198 | 0.6 | 99.70 | 2.23 | 16 | 28.0 | 25.094 |
| 11A | 129 | 0.008 | 99.99 | 1.94 | 25 | 26.0 | 25.145 |
| B | 156 | 0.1 | 99.94 | 1.99 | 25 | 26.0 | 25.145 |
| C | 199 | 0.04 | 99.98 | 2.23 | 25 | 26.0 | 25.145 |
| D | 324 | 0.04 | 99.99 | 2.10 | 25 | 26.0 | 25.145 |
| 12A | 143 | 0.6 | 99.58 | 2.04 | 19 | 32.5 | 25.089 |
| B | 158 | 0.2 | 99.87 | 2.81 | 19 | 32.5 | 25.089 |
| C | 988 | 0.1 | 99.99 | 6.80 | 19 | 32.5 | 25.089 |
| D | 545 | 0.1 | 99.98 | 6.04 | 19 | 32.5 | 25.089 |
| 13A | 205 | 0.3 | 99.85 | 2.56 | 19 | 32.5 | 25.089 |
| B | 233 | 0.1 | 99.96 | 2.54 | 19 | 32.5 | 25.089 |
| C | 459 | 0.1 | 99.98 | 4.85 | 19 | 32.5 | 25.089 |
| D | 087 | 0.2 | 99.97 | 7.81 | 19 | 32.5 | 25.089 |
| 14A | 200 | 0.2 | 99.90 | 2.53 | 25 | 25.0 | 25.179 |
| B | 115 | 0.1 | 99.91 | 1.53 | 25 | 25.0 | 25.179 |
| C | 347 | 0.3 | 99.91 | 1.94 | 25 | 25.0 | 25.179 |
| D | 184 | 0.1 | 99.95 | 3.84 | 25 | 25.0 | 25.179 |

TABLE D.2. contd

| Sample Location | Flux, pCi/m$^2$·S Before | Flux, pCi/m$^2$·S After | Flux Reduction, % | Before Seal: Tailings Moisture, % | Before Seal: Relative Humidity, % | Before Seal: Temperature Average °C | Before Seal: Barometric Pressure in Hg |
|---|---|---|---|---|---|---|---|
| 15A | 86 | 0.3 | 99.65 | 2.45 | 24 | 25.5 | 25.119 |
| B | 94 | 0.2 | 99.79 | -- | 25 | 25.0 | 25.179 |
| C | 157 | 0.2 | 99.87 | -- | 16 | 28.0 | 25.094 |
| D | 177 | 0.1 | 99.94 | -- | 16 | 28.0 | 25.094 |
| 16A | 116 | 0.0 | 100.00 | 2.05 | 25 | 26.0 | 25.145 |
| B | 134 | 0.2 | 99.85 | 2.40 | 25 | 26.0 | 25.145 |
| C | 189 | 0.02 | 99.99 | 2.23 | 25 | 26.0 | 25.145 |
| D | 126 | 0.002 | 99.99 | 2.47 | 25 | 26.0 | 25.145 |
| 17A | 170 | 0.04 | 99.98 | 2.02 | 17 | 34.0 | 25.001 |
| B | 139 | 0.008 | 99.99 | 3.13 | 17 | 34.0 | 25.001 |
| C | 183 | 0.02 | 99.99 | 2.16 | 17 | 34.0 | 25.001 |
| D | 147 | 0.03 | 99.98 | 2.50 | 17 | 34.0 | 25.001 |
| 18A | 162 | 0.4 | 99.75 | 1.72 | 16 | 31.0 | 24.988 |
| B | 143 | 0.4 | 99.72 | 2.27 | 16 | 31.0 | 24.988 |
| C | 183 | 0.1 | 99.95 | 3.08 | 16 | 31.0 | 24.988 |
| D | 162 | 0.0 | 100.00 | 4.97 | 16 | 31.0 | 24.988 |
| 19A | 137 | 0.01 | 99.99 | -- | 16 | 31.0 | 24.988 |
| B | 184 | 0.2 | 99.89 | -- | 16 | 31.0 | 24.988 |
| C | 172 | 0.1 | 99.94 | -- | 16 | 31.0 | 24.988 |
| D | 172 | 0.0 | 100.00 | -- | 16 | 31.0 | 24.988 |
| 20A | 258 | 0.2 | 99.92 | -- | 17 | 34.0 | 25.001 |
| B | 284 | 0.2 | 99.93 | -- | 17 | 34.0 | 25.001 |
| C | 313 | 0.03 | 99.99 | -- | 17 | 34.0 | 25.001 |
| D | 341 | 0.1 | 99.97 | -- | 17 | 34.0 | 25.001 |
| E | 589 | -- | -- | 13.45 | 24 | 25.5 | 25.119 |
| F | 176 | -- | -- | 6.45 | 24 | 25.5 | 25.119 |
| G | 251 | -- | -- | 1.35 | 24 | 25.5 | 25.119 |
| H | 216 | -- | -- | 1.86 | 24 | 25.5 | 25.119 |
| I | 169 | -- | -- | 1.49 | 15 | 32.5 | 25.073 |
| J | 123 | -- | -- | 3.30 | 15 | 32.5 | 25.073 |
| K | -- | -- | -- | 2.47 | 15 | 32.5 | 25.073 |
| L | 550 | -- | -- | 1.14 | 15 | 32.5 | 25.073 |

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