Asphalt Emulsion Radon Barrier Systems for Uranium Mill Tailings - An Overview of the Technology

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March 1984

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ABSTRACT

Pacific Northwest Laboratory (PNL), under contract to the U.S. Department of Energy (DOE) Uranium Mill Tailings Remedial Action Project (UMTRAP) office, has developed an asphalt emulsion cover system to reduce the release of radon from uranium mill tailings. The system has been field tested at Grand Junction, Colorado. Results from laboratory and field tests indicate that this system is effective in reducing radon release to near-background levels ($<2.5 \text{ pCi m}^{-2}\text{s}^{-1}$) and has the properties required for long-term effectiveness and stability. Engineering specifications have been developed, and analysis indicates that asphalt emulsion covers are cost-competitive with other cover systems. This report summarizes the technology for asphalt emulsion radon barrier systems.

SUMMARY

Pacific Northwest Laboratory (PNL), under contract to the U.S. Department of Energy (DOE) Uranium Mill Tailings Remedial Action Project (UMTRAP) office, is investigating asphalt emulsion cover technology to reduce the release of radon from uranium mill tailings. Results from this study have demonstrated that the asphalt emulsion cover system is effective in reducing radon release to near-background levels ($<2.5 \text{ pCi m}^{-2}\text{s}^{-1}$). Field tests indicated that the cover system has the properties required for long-term effectiveness and stability.

This report summarizes the technology development, consisting of laboratory and field studies. The laboratory studies included 1) seal formulation, 2) radon diffusion measurements, and 3) structural and chemical stability assessments. The field studies included 1) evaluating application technology, 2) field testing at the Grand Junction, Colorado, tailings pile, 3) monitoring the effectiveness of the covers, and 4) developing engineering specifications.

The overall results of this program are summarized below:

- Numerous asphalt cover systems were investigated, including asphalt emulsion sprayed-on seals, hot rubberized asphalt sprayed-on seals, and asphalt emulsion admix seals. The most consistently effective structurally stable seal was determined to be an asphalt emulsion admix seal ~6 to 8 cm thick consisting of cationic asphalt emulsion and a fine aggregate. The residual asphalt content necessary to fill all the voids and prevent radon transport was $\sim 22 \pm 5 \text{ wt\%}$.
- Radon flux reductions greater than 99% were achieved with a variety of asphalt cover systems. Diffusion coefficients, measured on both laboratory and field test samples, ranged from $\sim 10^{-4}$ to less than $10^{-6} \text{ cm}^2/\text{s}$; the diffusion coefficient for soil is typically about $10^{-2} \text{ cm}^2/\text{s}$.

- The chemical and structural properties of the admix seal were determined to be suitable for maintaining the long-term integrity of the seal. The effects of autooxidation, aqueous leaching, microbial attack, temperature cycling, and tailings subsidence were investigated.
- Many application techniques were reviewed and tested, including a cold mix paver, portable pug mill and standard paver, batch plant and paver, slurry sealer, soil stabilizer, transient mixer, distributor truck, and chip sealer. The most effective technique, based on ease of operation and resultant seal quality, was the cold mix paver. An admix ~12 cm thick was applied; and after curing for several days to a few weeks (depending on ambient air temperature), it was compacted to form the final seal.
- Three field tests were conducted at the tailings pile at Grand Junction, Colorado, to determine the effectiveness of the cover system:
 - 1979 soil stabilizer test (in situ addition of asphalt emulsion)
 - 1980 seal application tests, including soil stabilizer, multi-layer asphalt emulsion/sand seal using chip sealer, sprayed-on asphalt emulsion seal and hot rubberized asphalt seal, cold mix paver, continuous pug mill and paver, and transit mixer and paver
 - 1981 cold mix paver test.
- The results of the field tests indicated that all the seals that were applied provided an effective radon barrier and reduced the release of radon below the U.S. Environmental Protection Agency (EPA) standard of $20 \text{ pCi m}^{-2}\text{s}^{-1}$. However, the most consistently effective seal was that prepared by the cold mix paver in both the 1980 and 1981 field tests. Average radon fluxes from the 1980 and 1981 tests plots were less than $2.5 \text{ pCi m}^{-2}\text{s}^{-1}$ with flux reductions of 99.7% and 99.6%, respectively.

- Based on the results of the laboratory and field studies, engineering specifications were developed. These included materials specifications for asphalt emulsions, aggregates, and admixes, and construction specifications for site preparation, seal application, etc. The basic cover system consisted of a 6- to 8-cm thick admix seal of a cationic asphalt emulsion and a fine aggregate such as concrete sand. The admix seal was covered with local soil to a depth of ~0.6 m to protect the seal from weathering, thus providing a long-term stable cover system.

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INTRODUCTION

The milling of uranium ore generates large quantities of solid waste, or tailings, that contain residual radioactivity not removed during the milling process. The principal radionuclide present in the tailings is radium, which decays to radon gas. Radon is considered a potential health hazard if inhaled; and because radon will continue to be produced from the radium and thorium in the tailings, the U.S. Environmental Protection Agency (EPA) has established strict standards for disposal of these tailings, limiting the annual average release of radon gas to the air to $20 \text{ pCi m}^{-2}\text{s}^{-1}$ or 0.5 pCi/l at the site boundary.

Cost-effective technology was needed to meet this standard. Therefore, the U.S. Department of Energy (DOE) UMTRAP^(a) office requested that Pacific Northwest Laboratory (PNL)^(b) evaluate cover systems that would meet this standard and minimize the cost of remedial action. PNL selected the three most promising cover systems for evaluation: earthen covers, multilayer covers, and asphalt covers. The most consistently effective cover system was found to be the asphalt cover.

The asphalt emulsion cover technology program began at PNL in 1976; laboratory evaluations were conducted to determine the effectiveness of sprayed-on asphalt emulsion seals (Koehmstedt et al. 1977). In 1979, laboratory and field studies were resumed under UMTRAP sponsorship to examine asphalt emulsion sealing procedures and to evaluate seal effectiveness (Hartley et al. 1980). Based on the encouraging results of the study, work has continued on the development of the asphalt emulsion seal (Hartley et al. 1981a, 1983).

The 1979 laboratory studies determined that a radon flux reduction greater than 99% could be achieved using a thin (3 to 7 mm thick) sprayed-on cationic asphalt emulsion seal or an 8-cm compacted admix seal of tailings and emulsion containing 18 to 20 wt% residual asphalt. The study further determined that

(a) Uranium Mill Tailings Remedial Action Project.

(b) Operated for DOE by Battelle Memorial Institute.

because the physical and chemical properties of the tailings can affect seal quality, an admix seal needs an alternative fine aggregate source such as blown sand or concrete sand.

The 1979 field test at the Grand Junction, Colorado, uranium tailings pile demonstrated that if a soil stabilizer is used to apply the seal in situ, proper equipment operation and tailings preconditioning (water addition) before the adding of emulsion are important for an effective seal. Overall results of the study suggested that alternative seals and application techniques should be investigated.

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. After review and evaluation of application technology, the more promising techniques were field tested. The effectiveness of the seals was determined by measuring radon release before and after seal application. The long-term stability of the seal was tested to determine the effects of chemical (autooxidation, aqueous leaching) and physical (mechanical, freeze/thaw, animal intrusion, root penetration) degradation (Hartley et al. 1981a).

The results of the 1980 testing further demonstrated that asphalt emulsion/aggregate admix seals or sprayed-on seals were effective in reducing radon release to less than $2 \text{ pCi m}^{-2}\text{s}^{-1}$ (the proposed EPA standard in 1980). The most successful application procedure out of the seven tested at Grand junction used a cold mix paver to apply an admix containing cationic asphalt emulsion and concrete sand with a residual asphalt content averaging 23 wt%. Based on the successful results of the 1980 laboratory and field studies, further studies were recommended, including a comparative field test using earthen covers, multilayer covers, and the asphalt emulsion cover.

In 1981, laboratory and field studies were conducted to improve asphalt emulsion cover technology. The major emphases were on seal formulation to develop specifications for asphalt emulsions and aggregates, and on evaluation of the seal's long-term stability and application of a selected admix seal with a cold mix paver in the comparative field test (Hartley et al. 1983). Results

of the 1981 activities further verified the effectiveness of the asphalt emulsion admix seal as a radon barrier. Radon flux reductions were greater than 99% and resulted in an average flux of less than $2.5 \text{ pCi m}^{-2}\text{s}^{-1}$.

Since the comparative field test was initiated during the summer of 1981, the major emphases have been on establishing asphalt emulsion, aggregate, and application specifications; continuing to evaluate the long-term stability of the admix seal; and monitoring the 1979, 1980, and 1981 field tests.

The asphalt emulsion admix radon seal illustrated in Figure 1 is a radon gas barrier with desirable properties for long-term stability. The barrier system consists of a 6- to 8-cm thick asphalt emulsion/aggregate admix layer covered by ~0.6 m of overburden. The layer acts as a radon-impermeable diffusion barrier, and the overburden protects the admix seal. The admix is composed of cationic asphalt emulsion and fine aggregate such as concrete sand. After curing, the admix contains ~22 wt% asphalt on a dry aggregate basis and less than 1 wt% residual water.

This report summarizes the current state of asphalt emulsion cover technology, and includes the results of laboratory and field studies, long-term stability studies, and engineering specifications.

FIGURE 1. Asphalt Emulsion Admix Radon Barrier System

CHARACTERISTICS OF URANIUM MILL TAILINGS

Tailings are the finely ground residues from ore processing and are the principal wastes from uranium milling operations. They are a mixture of 70% to 80% coarse and fine sands and 20% to 30% silts and clays (slimes). The sands are silica with small amounts of complex silicates of Na, K, and Ca and heavy metals. The fine-grained slimes from acid-processed ore are primarily composed of Na, K, Ca, Mg, Al, and Fe silicates while those from alkaline leaching consist primarily of silica and various carbonates of Na, K, Ca, Mg, Mn, Al, and Fe with some sulfates. The composition of a typical inactive tailings pile (Grand Junction, Colorado) is shown in Table 1. Some additional characteristics of selected tailing samples are listed in Table 2.

TABLE 1. Chemical Composition of Grand Junction Tailings

<u>Element</u>	<u>Average, wt%</u>	<u>Range, wt%</u>
Si	26.7	21 to 33
Al	4.3	1.5 to 7.6
Ca	4.1	1.4 to 5.5
S	2.9	1.6 to 4.6
Fe	2.3	0.7 to 4.7
K	0.89	0.42 to 1.3
Ti	0.28	0.10 to 0.34
V	0.20	0.13 to 0.33
As	0.040	0.01 to 0.1
Ni	0.029	0.004 to 0.006
Sr	0.026	0.007 to 0.050
U	0.017	0.006 to 0.029
Pb	0.017	0.006 to 0.036
Cr	0.011	0.007 to 0.022
Zn	0.011	0.003 to 0.017
Mn	0.005	0.002 to 0.012
Cn	0.004	0.002 to 0.011
Ra	-	30 to 2500 ^(a)

(a) pCi/g.

TABLE 2. Characteristics of Selected Uranium Mill Tailings Samples

Tailings Sample	Prior			% Larger Than 10	% Smaller Than 200	
Site	Processing	pH	H ₂ O, %	Mesh	Mesh	Appearance
Shiprock, New Mexico	Acid	3.3	-	4	12	Sandy, containing 8- to 20-cm rock
Falls City, Texas	Acid	3.1	-	-	-	Slimes, sand, and clay composite
Tuba City, Arizona	Acid and carbonate	2.7	-	2	19	High clay content; very fine
Mexican Hat, Utah	Acid	5.0	-	-	-	Sand and slimes composite
Monument Valley, Arizona	Acid	5.5	-	3	1	Coarse sand and slime composite
Vitro, Salt Lake City, Utah	Acid	3.5	-	-	-	Sand, sludge, and slimes composite
Ambrosia Lake, New Mexico	Carbonate	9.1	-	-	-	Fine sand and clay
Grand Junction, Colorado	Acid	7.0	4.4	1	17	Sandy

The radioactive materials of concern in the tailings belong to the ^{238}U decay series. For the uranium series, ^{230}Th is the major parent nuclide in the tailings with an 80,000-yr half-life, although eventually the ^{238}U (4.5×10^9 yr half-life) in the tailings will control the series (Figure 2). The ^{230}Th will provide a long-term supply of ^{226}Ra , which will in turn provide a long-term supply of ^{222}Rn . Radon-222 (3.8-day half-life) continually escapes to the atmosphere; the rate depends on the distribution of ^{226}Ra in the tailings and their physical and chemical properties. The short-lived airborne alpha-emitting daughters of ^{222}Rn (^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po) pose a relatively low radiological risk to those living near the tailings pile.

The 24 inactive uranium mill tailings sites designated for remedial action under UMTRAP are located in 10 states (Table 3) and contain ~23 million metric tons of tailings. Nine of these sites have been classified as high priority for remedial action.

FIGURE 2. Uranium-Radium Family (Decay Chain for Uranium-238)

TABLE 3. Inactive U.S. Uranium Tailings Sites

<u>Site</u>	<u>Tailings, 1000 MT</u>	<u>Area, acres</u>	<u>Priority</u>
<u>Arizona</u>			
Monument Valley	1000	80	Low
Tuba City	730	88	Medium
<u>Colorado</u>			
Durango	1420	107	High
Grand Junction	1730	200	High
Gunnison	490	61	High
Maybell	2370	84	Low
Naturita	640	109	Medium
New Rifle	2460	300	High
Old Rifle	320	22	High
Slick Rock (NC)	34	160	Low
Slick Rock (UCC)	320	355	Low
<u>Idaho</u>			
Lowman	82	37	Low
<u>New Mexico</u>			
Ambrosia Lake	2370	165	Medium
Shiprock	1370	230	High
<u>North Dakota</u>			
Belfield	--	--	Low
Bowman	--	--	Low
<u>Oregon</u>			
Lakeview	118	228	Medium
<u>Pennsylvania</u>			
Canonsburg	200	19	High
<u>Texas</u>			
Falls City	2280	386	Medium
<u>Utah</u>			
Green River	112	80	Low
Mexican Hat	2000	555	Medium
Salt Lake City	1550	128	High
<u>Wyoming</u>			
Converse County	170	15	Low
Riverton	825	112	High

ASPHALT EMULSION TECHNOLOGY

As defined by the American Society for Testing and Materials (ASTM), asphalt is a dark brown to black cementitious material of which the predominating constituents are bitumens, which occur in nature or are obtained in petroleum processing. Asphalt is generally solid or semisolid at ambient temperature. A thermoplastic material, it gradually liquefies as it is heated. Asphalt can also be maintained in a fluid-like state by mixing with a light hydrocarbon solvent (cutback asphalt) or with water and an emulsifier (asphalt emulsion). Asphalt emulsions appear to form the most effective radon barrier seal.

ASPHALT EMULSION CHEMISTRY

Asphalts are colloidal dispersions of high-molecular-weight aromatic hydrocarbons called asphaltenes. These asphaltenes are dispersed in a continuous phase of lower-molecular-weight oily resinous material (paraffins and aromatic resins) called maltenes. As such, asphalt normally will not mix with water. However, given the proper concentrations of special surface active agents (emulsifiers), homogeneous mixtures of small asphalt droplets suspended in a continuous water phase can be produced. These are referred to as asphalt emulsions. The three chemical components of asphalt emulsions--asphalt, water, and emulsifier--are mixed in a high-speed, high-shear mechanical device such as a colloid mill. Asphalt usually accounts for 55% to 70% of the mixture.

The emulsifier or surfactant is the most important component of any asphalt emulsion. Effective emulsifiers possess the unique property of altering the surface energy of their solvents and usually lower rather than increase the surface energy. These chemicals are soluble substances that markedly change the properties of the solvent and the surfaces they contact. When used with an acceptable asphalt, a good-quality water, and adequate mechanical input, the emulsifier is the major factor in initial emulsification, emulsion stability, and ultimate field performance.

Asphalt emulsions are divided into three classes: anionic, cationic, and nonionic. The anionic and cationic classes refer to the electrical charges

surrounding the asphalt particles. An anionic emulsion contains negatively charged particles that would be attracted to an anode. A cationic emulsion contains positively charged particles that would be attracted to a cathode. In this report the letter "C" will be used to describe cationic emulsions; the absence of a "C" will indicate that the emulsion is anionic or nonionic. Emulsions are further classified on the basis of how quickly the asphalt will coalesce (revert to asphalt cement). Asphalt coalescence is commonly referred to as breaking or setting. The rate at which the asphalt globules separate from the water is referred to as breaking or setting time. The relative terms "rapid setting" (RS), "medium setting" (MS), and "slow setting" (SS) have been adopted to simplify and standardize classification. Thus, a cationic slow-setting emulsion would be referred to as CSS. The tendency to coalesce is closely related to the mixing of an emulsion. An RS emulsion has little or no ability to mix with an aggregate, an MS emulsion is expected to mix with coarse but not fine aggregate, and an SS emulsion is designed to mix with fine aggregate.

After an asphalt emulsion has been applied, the asphalt must separate from the water to perform its intended function. For surface treatments and seals, emulsions are formulated to break up on contact with a foreign substance such as aggregate or a pavement surface. The asphalt droplets coalesce and produce a continuous film of asphalt on the aggregate or pavement. For dense mixtures, more time is needed to allow for mixing and laydown. Therefore, emulsions used for mixtures are formulated for delayed breaking.

Both anionic and cationic asphalt emulsions depend on the evaporation of water for development of curing and adhesion characteristics. Water displacement can be fairly rapid under favorable weather conditions; but high humidity, low temperatures, or rainfall soon after application can inhibit proper curing. Traditional theory holds that anionic emulsions (with a negative charge on the asphalt droplets) perform best with aggregates having mostly positive surface charges; also, that cationic emulsions (with a positive charge on the asphalt droplets) perform best with aggregates having mostly negative surface charges (for example, siliceous or granitic aggregates). Presently, however, there is not complete agreement with this theory.

When using either the anionic or cationic RS emulsions, the initial asphalt deposit develops through an electrochemical phenomenon. The strongest bond between the asphalt film and the aggregates forms after the loss of emulsifying water. This water film can be displaced by evaporation, pressure (rolling), or absorption; in actual use, curing is usually a combination of all three.

ASPHALT EMULSION HISTORY

Asphalt deposits have been utilized by man for centuries. Some deposits are in the form of tar sands (for example, Athabasca Tar Sands in Alberta, Canada), pits or springs (for example, Rancho-la-Brea Asphalt Pits in California and Al-Kwait in Arabia), or rock asphalt (Valde Country, Texas). The majority of asphalt used today results from crude oil refining.

The earliest recorded use of asphalt (about 3800 B.C.) was by the pre-Babylonian inhabitants of the Euphrates Valley in southeastern Mesopotamia (presently Iraq). According to legend, the infant King Sargan was placed in a reed basket coated with asphalt and set adrift on the Euphrates River (Rogers 1912; McKenzie 1916). The earliest recovered asphalt item was the bust of Manishtusu, King of Kish (about 3600 B.C.) (de Morgan 1907; Langdon 1927), found in excavations at Susa, Persia. The limestone eyes were held in place with asphalt. From the 3500 to 2900 B.C. era, numerous ornaments,^(a) figurines (Fish 1934; Woolley 1934), statues (Jastrow 1915), ceremonial baths (Nellensteyn and Brand 1936), and pavements (Frankfort 1934; Falkenstein 1936) that made some use of asphalt have been excavated. These objects were recovered in excellent condition, attesting to the long-term stability of asphalt under anaerobic burial conditions.

The use of asphalt emulsions for road construction and maintenance was first developed in the early 1900s. It was not until the 1920s, however, that emulsions, as we know them today, came into being. Their early use was confined largely to spray applications and to dust palliation.

(a) Hackford, Lawson, and Spielman (1931); Hall and Woolley (1927); Forbes (1936); Woolley (1930); Langdon (1928).

Records reveal a slow but steady increase in emulsion use between 1930 and the mid-1950s. Following World War II, traffic loads and volumes increased so much that road designers began to curtail the use of these materials. Instead, they specified hot plant mixes requiring the use of asphalt cement. While the volume of asphalt cement used has shown a rapid increase since 1953, the combined use of other asphalt products has remained almost constant.

The major uses of asphalt emulsion in the United States are:

- surface treatments
- patching and thin overlays
- stabilization
- slurry sealing
- base and surface coarse mixes.

In the past few years, several factors have contributed to a nationwide interest in the use of asphalt emulsions:

- The energy crisis of the early 1970s prompted conservation measures by the Federal Energy Administration. Asphalt emulsion does not require a petroleum solvent to make it liquid (however, some MS grades contain limited amounts of solvent to enhance mixing qualities). Asphalt emulsion can also be used (in most cases) without additional heat. Both of these factors contribute to energy savings.
- There are few or no atmosphere-polluting hydrocarbon emissions from asphalt emulsions.
- Certain types of asphalt emulsion can coat damp aggregate surfaces--another energy-saving feature.
- A greater number of emulsion types are available and laboratory procedures have been improved to satisfy design and construction requirements.
- Cost savings are possible because no solvent is used.

In 1979, the Federal Highway Administration issued notices directing attention to fuel savings that could be realized by using asphalt emulsions

instead of cutback asphalts. They estimated that huge amounts of petroleum solvents could be saved annually by such substitution, and it was strongly suggested, although not mandated, that this option be considered. At least 42 states were then substituting, or allowing the substitution of, asphalt emulsions for other asphalt types, and it is probable that the number has since increased (Asphalt Institute 1979).

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increased (Asphalt Institute 1979).

LABORATORY STUDIES

The overall objective of the laboratory studies conducted in this program was to develop an effective asphalt emulsion seal that could be expected to contain radon for a long period of time. The primary activities included seal formulation and testing and development of mix design procedures.

SEAL FORMULATION AND TESTING

The concept as originally conceived at PNL consisted of spraying or pouring a thin layer (3 to 10 mm) of asphalt emulsion directly over the uranium mill tailings. Because of concern over the mechanical strength of such a seal, the concept evolved into the use of a thicker (5 to 10 cm) asphalt/aggregate admixture as a seal.

Several asphalt emulsions were used in the seal development studies. Satisfactory admixes were made with most of the emulsions, as indicated in Table 4. During the course of the seal development studies, it became apparent that making a satisfactory admix seal required the proper choice of aggregate, asphalt emulsion, and mixing conditions. Emulsions supplied primarily by Armac were used for the seal development studies. These emulsions worked quite well and many different types were available. Over the course of the laboratory studies, various methods of evaluating the test specimens were used as the techniques for measuring radon diffusion were refined.

Seal Development Studies

Cationic asphalt emulsions (CSS emulsion) were prepared with Armac Redicote E-63, E-65, and E-4868 emulsifiers. The seal specimens were made by pouring the emulsion over tailings from eight uranium mill tailings sites. Very high flux reductions were achieved with all of the test samples, indicating that only a thin layer of asphalt is necessary to contain radon emissions (Table 5). However, these thin seals are not physically strong enough to be considered permanent; therefore, admix seals were investigated. A typical admix specimen that was made and tested in the laboratory studies is shown in Figure 3.

TABLE 4. Emulsions Used in Seal Development Studies

Supplier	Identification	Satisfactory Admix
Armak	E-63 (CSS)	Yes
	E-65 (CSS)	Yes
	E-4868 (CSS)	Yes
	56 mV (CMS)	Yes
	62 mV (CMS)	Yes
	78 mV (CMS)	Yes
	93 mV (CRS)	Yes
Chevron	79R 3416	No
	QS-h	Yes
	CSS-1	No
	QS-K-h	Yes
	CQS	Yes
Union 76	CMS	Yes
U.S. Oil	CMS	No

TABLE 5. Radon Flux Reduction Using Poured Asphalt Emulsion Seals

Tailings Sample Site	Seal Thickness, mm	Relative Radon Flux Reduction, %
Vitro, Salt Lake City, Utah	3	99.9
Ambrosia Lake, New Mexico	5	99.9
Mexican Hat, Utah	5	99.3
Monument Valley, Arizona	8	99.8
Shiprock, New Mexico	5	99.9
Tuba City, Arizona	5	99.9
Falls City, Texas	5	99.9
Grand Junction-1, Colorado	9	99.9 (pressurized seal)
Grand Junction-3, Colorado	9	99.9 (pressurized seal)
Grand Junction-4, Colorado	9	99.9 (pressurized seal)

FIGURE 3. Example of Laboratory Asphalt Admix Specimen

Admixtures of Grand Junction tailings and asphalt emulsion containing 8 to 20 wt% residual asphalt were tested for their ability to contain radon. Some typical results are shown in Table 6. Admixes containing 10 to 12 wt% residual

TABLE 6. Effect of Asphalt Content on Radon Diffusion Through Admix Seals^(a)

<u>Residual Asphalt Content, wt%</u>	<u>Relative Radon Flux Reduction, %</u>
10	Seal failed
13.5	Seal failed
15	~50%
18 to 20	>99%

(a) Seals were ~8 cm thick and were made with a CSS emulsion using Armak 4868.

asphalt stopped neither water vapor nor radon; admixes containing 12 to 14 wt% residual asphalt appeared to seal out only water vapor. Starting at a residual asphalt content of 14 wt%, a marked reduction in radon flux (~50%) was noted. With 18 to 20 wt% residual asphalt, radon flux was reduced by more than 99.9%.

The effectiveness of admix seals made with tailings from several selected sites is shown in Table 7. Some problems were encountered with Tuba City, New Rifle, and Shiprock tailings. The problems appeared to be primarily related to the particle size distribution of the tailings (see Table 8).

Particle size distribution of the seal aggregate is an important parameter in forming a gas-tight seal. It affects the ability of the emulsion to mix with the tailings and 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. In addition, the fraction larger than 50 mesh (medium sand) also seems important. New Rifle samples 1 and 3 and Shiprock sample 1 caused the most problems. All three samples had less than 10% larger than 50 mesh. Good seals were made with both Shiprock sample 4 and Tuba City sample 1 despite the large percentage smaller than 200 mesh. Both of these samples had more than 20% larger than 50 mesh.

TABLE 7. Radon Flux Reduction with Admixes Made from Tailings and Armak 4868 (CSS)

Aggregate Source	Residual Asphalt Content, wt%	Relative Radon Flux Reduction, %
Grand Junction	15	50
Grand Junction	17.6	>99
Grand Junction	20.0	>99
Tuba City	25.0	88 to 99
Tuba City	29.5	99
Shiprock	17.6	62 to 97
Shiprock	25.0	>99
New Rifle	32 to 48	Seal failed

TABLE 8. Particle Size Distribution of Tailings

Sieve Size	% Passing								Concrete Sand
	Grand Junction		Shiprock		New Rifle		Tuba City		
	1	2	1	4	1	3	1	2	
3/8	-	-	-	-	-	-	-	-	100
4	-	-	-	-	-	-	-	-	99
8	-	-	-	-	-	-	-	-	88
16	99	99	100	87	100	100	98	76	73
30	98	98	100	80	100	100	83	70	56
50	82	90	85	76	100	91	58	60	27
100	40	65	57	69	90	45	35	22	6
200	8	38	30	59	58	20	21	7	2

Because of the large variability in the tailings samples several other types of aggregate were tested. The flux reductions using these aggregates are shown in Table 9. Based on effectiveness and availability, concrete sand was selected as the standard aggregate to be used for further laboratory and field studies. Cost studies showed that using concrete sand instead of tailings would increase the cost of the seal by no more than 5%.

Local concrete sand was obtained from five tailings locations (Salt Lake City, Grand Junction, Durango, Rifle, and Riverton) for further testing.

TABLE 9. Radon Flux Reductions for CSS Emulsion Admixes Using Armak 4868 and Selected Aggregates

Admix	Residual Asphalt Content, wt%	Relative Radon Flux Reduction, %
Hanford blown sand	22.0	Seal failed
Hanford blown sand	24.6	>99
Crushed rock, smaller than 1 cm	13.6	Seal failed
Crushed rock, smaller than 1 cm	17.6	>99
Grand Junction concrete sand	25.8	>99
Tri-City concrete sand	22.0	>99
Grand Junction concrete sand	22.0	>99

Asphalt/aggregate admixes were made with the concrete sands and asphalt emulsion from the supplier closest to each site. Test results for these specimens are discussed in the Engineering Specifications section.

Laboratory Radon Diffusion Measurement System

The ability of the asphalt seal to inhibit radon transport is best described by the diffusion coefficient for radon through the seal. The radon diffusion coefficient can be measured in the laboratory using a relatively small sample. A known concentration of radon gas is passed under the barrier, and any radon that diffuses through the barrier is collected. A one-dimensional transient diffusion computer code is then used to compute the diffusion coefficient.

Radon diffusion coefficients were measured using the test setup shown in Figure 4. Nitrogen is passed through 120 mCi RaCl_2 in HCl to generate 100 $\mu\text{Ci}/\ell$ ^{222}Rn . This gas is passed at 75 cm^3/min to each of two 6-in.-diameter Lucite® cells containing the asphalt seal. The flow of this ^{222}Rn /nitrogen mixture maintains the concentration at ^{222}Rn below the seal at 100 $\mu\text{Ci}/\ell$. Nitrogen at 50 cm^3/min is passed over the top of the seal to collect any radon that diffuses through it. The gas then passes through a bed of activated carbon that traps >99% of the radon. The test is conducted for 1 to 7 days depending on the type of seal being tested. The activated carbon is removed from the tubes, placed in Petri dishes, and allowed to equilibrate for at least 4 h. The activated carbon is then counted using an intrinsic germanium diode coupled to a multichannel analyzer, and the ^{214}Bi daughter of radon (609 keV) is used to determine the activity of the radon passing through the seal. The radon concentration below the seal in the bottom of the cell is also determined by sampling and counting.

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FIGURE 4. Radon Diffusion Coefficient Measurement Test Apparatus

These data along with the sample area, thickness, porosity, and moisture content are used as input to the PNL computer code SEARCH. SEARCH is a one-dimensional transient, basic-diffusion code that adjusts the diffusion coefficient for the seal until the predicted surface flux results in a radon accumulation matching the amount obtained experimentally. This output value is the bulk diffusion coefficient, D_e .

Laboratory Radon Diffusion Results

Some results of radon diffusion testing on pure asphalt and admix samples are shown in Table 10. For those samples made with tailings, the diffusion coefficient ranged from about 10^{-1} to 10^{-4} cm^2/s . Samples made from the New Rifle tailings would not seal. The diffusion coefficient for admixes made with

TABLE 10. Radon Diffusion Coefficients for Laboratory Prepared Asphalt Seals

Pure Asphalt Seal	Aggregate	Asphalt Content, wt/wt Dry Aggregate	Seal Thickness, cm	Diffusion Coefficient (D_e), cm^2/s
Asphalt Cement No. 1	None	--	~1 cm	4.4×10^{-7}
Asphalt Cement No. 2	None	--	~1 cm	1.6×10^{-6}
Asphalt Cement No. 1 under 0.3 psi pressure	None	--	~1 cm	2.3×10^{-6}
Asphalt Cement No. 2 under 0.3 psi pressure	None	--	~1 cm	2.8×10^{-6}
<u>Admixes Made with Tailings</u>				
Armak 4868	Tuba City 1	0.29	11.8	3.8×10^{-1}
Armak 4868	Tuba City 2	0.25	9.2	2.7×10^{-2}
Armak 4868	Tuba City 3	0.25	10.5	2.7×10^{-3}
Armak 4868	Tuba City 3	0.29	11.1	1.3×10^{-3}
Armak 4868	Shiprock 1	0.17	8.9	1.4×10^{-1}
Armak 4868	Shiprock 1	0.28	9.5	1.8×10^{-4}
Armak 4868	Shiprock 2	0.25	9.2	4.5×10^{-3}
Armak 4868	Shiprock 3	0.17	8.2	4.0×10^{-3}
Armak 4868	Shiprock 3	0.25	10.5	2.0×10^{-4}
Armak 4868	New Rifle	0.39 to 0.58	15.4	Failed pressure test
<u>Admixes Made with Concrete Sand</u>				
Armak 4868	Grand Junction	0.21	7.6	1.9×10^{-4}
Armak 4868	Grand Junction	0.21	7.6	1.0×10^{-4}
Armak 4868	Grand Junction	0.21	7.6	1.4×10^{-4}
Conoco with 1% Tyfo A	Rifle	0.22	3.7	6.1×10^{-5}

TABLE 10. (contd)

Admixes Made with Concrete Sand	Aggregate	Asphalt Content, wt/wt Dry Aggregate	Seal Thickness, cm	Diffusion Coefficient (D_e), cm^2/s
Conoco with 1% Tyfo A	Grand Junction	0.22	4.0	5.3×10^{-5}
Conoco with 1% Tyfo A	Durango	0.22	3.7	2.6×10^{-5}
Utah Emulsion with 1% Tyfo A	Vitro	0.22	3.7	1.7×10^{-4}
Utah Emulsion with 1% Tyfo A	Riverton	0.22	3.7	1.8×10^{-5}
Foamed hot asphalt	Blown sand	0.30		1.1×10^{-5}
<u>Other Admixes</u>				
Armak 78 mV	Sand	0.22	7.6	3.4×10^{-6}
Armak 78 mV	Sand	0.22	7.6	4.4×10^{-6}
Armak 78 mV	Sand	0.22	7.6	4.9×10^{-6}
Arco 2400	Sand	0.22	7.6	4.4×10^{-6}
<u>Miscellaneous</u>				
Hot asphalt	Hydraulic mix	0.11	7.6	2.0×10^{-6}
Hot asphalt	Hydraulic mix	0.11	7.6	3.4×10^{-6}
Hot asphalt	Macadam mix	0.23	7.6	2.0×10^{-6}
Hot asphalt	Macadam mix	0.24	7.6	2.3×10^{-6}
CRS macadam mix	Set emulsion	0.20	7.6	4.2×10^{-6}

local concrete sand from five sites and various asphalts had diffusion coefficients of $\sim 10^{-4}$ to 10^{-5} cm^2/s , which are lower than the D_e from the best admixes made with tailings.

Table 11 shows diffusion coefficients measured for some of the samples taken from the Grand Junction field test. The lowest diffusion coefficient was for the hot rubberized asphalt, followed by the cold mix paver and the soil stabilizer.

MIX DESIGN PROCEDURES

Laboratory studies indicated that an asphalt/aggregate admixture containing $\sim 22 \pm 5$ wt% residual asphalt is an effective radon barrier. The purpose of the mix design studies was to develop formulations that could be mixed and applied with commercial field equipment.

When an aggregate is mixed with a controlled set emulsion, the mixture sets up after a certain period of time. The admixture must remain workable while it is mixed and applied; and, after application, it must set at a reasonably fast rate. There are mix design procedures for asphalt emulsion paving mixtures (Fong 1978) and for slurry seal systems (Harkness 1977). However, neither of these systems is quite like the asphalt emulsion radon seal, and there were no procedures for determining the mix time and the set time. The

TABLE 11. Diffusion Coefficients for Samples Taken from Grand Junction Field Test Plot

Field Test	Date Sampled	Sample	Seal Thickness, cm	Diffusion Coefficient (D_e), cm^2/s
1979	1983	Soil stabilizer	11.1	8.0×10^{-4}
1980	1983	Soil stabilizer	11.4	4.1×10^{-4}
1980	1983	Rubberized asphalt	1.8	6.3×10^{-6}
1980	1983	Cold mix paver	7.0	2.2×10^{-4}
1981	1983	Cold mix paver	5.5	7.0×10^{-5}
1981	1981	Cold mix paver	5.9(a)	$4.7 \times 10^{-6}(a)$

(a) Average of seven samples.

goal of this phase of the program was to develop a laboratory mix design procedure that could be used by commercial or field laboratories to measure the mix time and set time for an asphalt emulsion seal.

Development of Mix Design Classification Test

A procedure was developed that eliminates subjective estimates of set time and replaces them with an objective measurement that detects the increasing stiffness of a setting admix. The method works very well and provides much insight into the setting properties of the asphalt emulsion/aggregate systems.

The aggregate that was used during the development of the test method was from Spokane, Washington (Tristate). The aggregate used in the 1981 field test at Grand Junction was used in later studies on the effect of aggregate on mix time and set time. The gradation of both aggregates is shown in Table 12.

The asphalt emulsions used in the development of the test procedure were one supplied by Armac (+78 mV zeta potential) and several made with Tyfo A and Tyfo B.^(a) The total emulsifier content of the Tyfo mixtures was 1%. The ratios of A to B were 100:0, 75:25, and 50:50; and various base asphalts were used.

TABLE 12. Aggregate Gradations (Washed)

<u>Aggregate Sieve, in.</u>	<u>Tristate, % Passing</u>	<u>Grand Junction, % Passing</u>
1/4-in.	100	100
4	100	99.1
8	79.4	75.1
10	73.9	64.5
30	35.6	54.5
40	28.2	11.7
100	16.3	7.9
200	12.4	3.1

(a) Manufactured by the National Research and Chemical Company.

The test procedure consisted of mixing the asphalt emulsion with aggregate in a specially designed apparatus (Figure 5) powered by a synchronous motor (the speed could be varied from 0 to 3000 rpm). The motor provided a torque feedback that was required to maintain a constant rpm during the mixing and setting process. The torque was recorded over time to provide a profile of the mixing and setting phenomena. The mixer was started empty at 50 rpm, the pre-moistened aggregate was then placed in the container, followed by the emulsion. If a retarder was used to increase setting time, it was added when the aggregate was premoistened. The torque from mixing was recorded, and the mix time and set time were determined from the graph. The mix time was defined as the time during which the curve of torque versus time is horizontal. The set time was defined as the time, after the addition of emulsion, when the torque/time profile approached vertical, as shown in Figure 6a. The test method as developed is included as Appendix A.

To obtain adequate precision, the gradation of the aggregate samples and the temperature were very closely controlled. Gradation will affect set time and, as the setting process is a chemical reaction, set time would be expected to vary exponentially with temperature. To ensure that each sample had the same gradation, the aggregate was separated by sieve size, and then each sieve size was recombined to the original gradation.

FIGURE 5. Mix Design Test Apparatus

It was also necessary to condition the aggregate at the test temperature, especially when tests were run at other than ambient temperature. The emulsion, container, and mixer were also preconditioned at the desired temperature so that minor temperature variations would not change the set times.

Setting Characteristics of Emulsion/Aggregate Mixture

Typical curves recorded during the admix setting process are shown in Figure 6. A typical graph of the desired type of set is shown in Figure 6a.

There are three distinct sections in the curve of an adequate set. The first section is horizontal and lasts anywhere from 30 s to a few minutes. This portion can be defined as a true mixing time. The second section starts

FIGURE 6. Types of Sets Observed During Mix Design Test

as a slight upward discontinuity after which the curve increases linearly for a period. After that the third section begins and the curve increases exponentially until the motor stalls and setting occurs. This process is described mathematically in Appendix A.

Three types of undesirable setting behavior were observed. Under some conditions, the consistency of the mix never does increase sufficiently to obtain a true set but goes instead into what is called a false slurry, in which the consistency increases to a maximum and then decreases. When false slurry occurs (Figure 6b), the structure is too weak to set well and is broken down from shear. It is often very difficult to observe this behavior during mixing in the field; however, it causes many problems in the working of joints. The common field remedy is to add more water, which only hides the problem; and the additional water may float emulsion to the surface.

The curve in Figure 6c describes a set that is occurring too rapidly. The initial portion (the mixing time) is very short; the curve then increases very rapidly until the motor stalls. This type of behavior suggests that there would not be sufficient time to work the joints when the mix is placed in the field.

The third undesirable setting behavior is a "weak set"; that is, the mix sets harder than a false slurry but not hard enough to stall the mixing equipment (Figure 6d). Continued mixing strips the asphalt off the aggregate. This type of set generally does not occur in the field because of the fast mixing time, but it may be observed in the laboratory. The significance is that such structures are weaker than is desirable and would remain tender longer than the strong set.

This mix design test makes it possible to objectively evaluate various asphalt emulsion/aggregate formulations and the effects of mixing variables such as temperature and water content. The mix design test can be used to help select the asphalt and aggregate for a specific commercial application and to predict how the admix will perform in field applications.

Formulation Studies

The objective of the formulation studies was to determine the effect of several variables on the setting properties of the asphalt emulsion/aggregate

system. The following variables were evaluated: emulsion formulation (asphalt, emulsifier, retardant), temperature, base asphalt from several sources, aggregate from several sources, and water quantity.

The effect of emulsion formulation and asphalt base stock on the setting and mixing times of a local aggregate is shown in Table 13. The setting properties of the emulsion could be varied over a wide range. The Armak +78 mV emulsion showed certain setting characteristics with a base asphalt from Utah Emulsions. With the Tyfo A and B emulsifiers, the setting characteristics could be adjusted from those of a CSS asphalt emulsion (which does not set at all) to those of some emulsions that had extremely fast sets. In the emulsions shown in Table 13, 4% to 8% aluminum sulfate solution was added as a retardant, except where noted. Thus, within each of these emulsion types, the mix and set times can be varied to account for temperature changes in the field.

TABLE 13. Effect of Emulsion Formula and Asphalt Base Stock on Mixing and Setting Times^(a)

Asphalt	Time, min					
	Armak 78 mV		Ratio of Tyfo A to Tyfo B			
	Mix	Set	100:0		75:25	
			Mix	Set	Mix	Set
Unknown	0.96	4.25	-	-	-	-
Tristate	-	-	0.4	2.8	0.45	4.1
U.S. Oil	-	-	0.45	8.5 ^(b)	8.85	(b)
Douglas Oil	-	-	Immediate set		Immediate set	
Chevron	-	-	0.35	8.6	1.1	9.0
Exxon	-	-	<0.4	0.6 ^(c)	0.6	4.1
Continental	-	-	Immediate set		0.45	2.5
Phillips	-	-	<0.2	2.75	0.6	9.7

(a) Temperature = 77°F; local aggregate used.

(b) Went into false slurry.

(c) Setting occurred almost immediately.

The setting properties of various emulsions made with a wide range of asphalt base stocks are also shown in Table 13. The base asphalt had a very strong effect on the setting properties of the emulsion. The aggregate source also had quite a strong effect, probably due to differences in aggregate surface charge and surface area. Thus, for any one site, the asphalt and aggregate that would be used at that site must be available so that a formula can be developed to match the base asphalt with the base aggregate.

Table 14 presents data on the effects of temperature and the addition of retarder to the mixing and setting times of asphalt/aggregate mixtures. Grand Junction aggregate was used in this experiment. As the table shows, temperature had a marked effect on the mixing and setting times, although this can be compensated for, to some extent, by adding a retarder. Setting is caused by a chemical reaction; it can therefore be expected to be sensitive to temperature as are all kinetic phenomena.

The marked effect of aggregate on mixing and setting times is shown in Table 15. Tristate (Spokane, Washington) and Grand Junction, Colorado, aggregates were used. The gradations of these aggregates are shown in Table 12.

The effect of water on mixing and setting times is shown in Table 16. Addition of water increased the set time significantly.

TABLE 14. Effect of Temperature and Retarder on Mixing and Setting Times^(a)

Temperature, °F	Time, min							
	0% Retarder ^(b)		1.0% Retarder		2.0% Retarder		3.0% Retarder	
	Mix	Set	Mix	Set	Mix	Set	Mix	Set
60	2.35	8.5	8.3	18.0	-	-	-	-
70	1.5	6.2	2.0	13.5	6.1	25.8	-	-
80	0.80	1.67	1.30	4.55	1.37	8.2	1.6	10.2

(a) Grand Junction aggregate.

(b) 8% $\text{Al}_2(\text{SO}_4)_3$ solution.

TABLE 15. Effect of Aggregate on Retardant Required to Meet Setting-Time Specifications^(a)

Sample	Aggregate	% $\text{Al}_2(\text{SO}_4)_3$ ^(b)	% H_2O	Mix Time, min	Set Time, min
141A	Tristate	4	0	1.3	4.5
B	Tristate	4	0	1.0	4.4
C	Tristate	4	0	0.6	4.0
Average				0.97	4.3
160A	Grand Junction	1	2	1.45	5.30
B	Grand Junction	1	2	1.20	4.65
C	Grand Junction	1	2	1.25	3.70
Average				1.30	4.55

(a) Tests conducted at ambient temperatures. The temperature of the Grand Junction aggregate was 3° F higher than that of the Tristate aggregate, yet less retarder was required. 35% emulsion was used.

(b) With 2% $\text{Al}_2(\text{SO}_4)_3$ solution, the mixing and setting times with Grand Junction aggregate were 1.4 and 8.2 min respectively. With 3% $\text{Al}_2(\text{SO}_4)_3$ solution, the times were 1.5 and 10 min. The Grand Junction aggregate is a much slower-setting aggregate than the Spokane aggregate.

TABLE 16. Effect of Water on Mixing and Setting Times on Armak 78 mV Emulsion^(a)

% H_2O	% Retarder	Mix Time, ^(b) min	Set Time, min
0	1	0.93	2.61
1	1	1.3	6.0
2	1	1.7	6.7
3	1	--	7.6
0	2	1.1	7.3
1	2	--	11.1
2	2	--	14.2

(a) Tests conducted at ambient temperature using 8% $\text{Al}_2(\text{SO}_4)_3$ as retarder.

(b) Mix times are quite difficult to determine at high water contents.

The data obtained from this study on the mixing of aggregate and asphalt emulsion show that it is very important to control temperature, gradation, and other variables to obtain meaningful setting and mixing times. Without such control, the error in the testing can greatly reduce the value of the data. These data also show quite conclusively that the type of asphalt (that is, the crude from which asphalt was made) and the aggregate have a very strong effect on the setting properties of the system. The emulsions will therefore have to be formulated to match the asphalt and aggregate used on the job. These studies have also shown that the setting time can be adjusted through formulation and by adding retarder; however, there is some concern over the effect of retarders on the long-term stability of the seal. While no confirming data exist, J. Dybalski of Armac suggests that the retarder may weaken the bond between the asphalt and aggregate. Therefore, the setting characteristics of the admix should be adjusted by changes in the formulation whenever possible.

FIELD STUDIES

Field tests were conducted to determine the effectiveness of the asphalt emulsion radon barrier systems developed by PNL. Various application techniques and equipment were evaluated, and the most promising were field-tested at the Grand Junction, Colorado, tailings site from 1979 through 1981. An improved radon flux field measurement system was also developed to measure the effectiveness of each of the seals.

EVALUATION OF APPLICATION TECHNIQUES AND EQUIPMENT

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

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

The first option considered was a thin coat of asphalt emulsion sprayed on the tailings surface. This technique would provide an effective radon seal with the least expense. Two sprayed-on seals were tested, an asphalt emulsion seal and a hot rubberized asphalt seal. However, the long-term mechanical stability of these seals was suspect; and emphasis came to be placed on techniques for applying asphalt/aggregate admixtures. Criteria were established for selecting application equipment based on the ability to apply a mechanically stable radon-tight seal. The equipment had to be able to mix and apply an admixture consisting of a fine aggregate and 30 to 40 wt% asphalt emulsion (18 to 24 wt% residual asphalt). The equipment had to apply the mix while

operating on up to a 20% slope. The technique should require only minimal base preparation, and the equipment should be commercially available with minimal modifications.

From the initial screening, the following equipment was selected for further review:

- soil stabilizer
- cold mix paver
- portable pug mill and paver
- transit mixer
- slurry seal machine
- chip sealer
- pneumatic gun
- drum dryer and paver
- batch plant and paver
- blade mixing and windrowing.

Soil Stabilizer. A hydrostatic-drive soil stabilizer was the first type of application equipment selected for field testing. The soil stabilizer mixes asphalt emulsion and aggregate (tailings in this case) in situ, eliminating aggregate hauling costs. It can apply up to ~25 wt% residual asphalt without equipment modifications. It is used primarily to prepare pavement bases and to recycle old asphalt pavement. The soil stabilizer shown in Figure 7 was field tested in 1979 and 1980.

Cold Mix Paver. The cold mix paver is designed as a combination aggregate/asphalt emulsion mixer (pug mill) and aggregate/asphalt emulsion admixture laydown machine. Currently, its primary commercial use is for open-graded road pavements (i.e., pavements designed with a broad-size-range aggregate but with few fines). Based on a review of its operating characteristics and observations made at screening tests in Colfax, California, and Holbrook, Arizona, the Midland 701 cold mix paver (shown in Figure 8) was selected for the 1980 and 1981 field tests. The cold mix paver has several characteristics that are desirable for applying an asphalt/aggregate radon barrier system:

FIGURE 7. Hydrostatic Soil Stabilizer

FIGURE 8. Cold Mix Paver

- designed for use with asphalt emulsions
- on-site mixing and laying, thus avoiding admixture handling problems
- short mixing time, which allows the use of faster-setting emulsions and lowers the potential for emulsion run-off
- semicontinuous operation
- potential production rate of 1500 tons of admix per day
- easily and instantaneously adjustable screed, permitting more accurate control over seal depth
- easily modified to obtain high asphalt concentrations.

The screening tests also identified some areas that would require attention before the unit was field tested:

- Substantial base preparation was required to support the front wheels on the cold mix paver.
- Calibration and precision of the asphalt emulsion pump and aggregate feed mechanism had to be improved.
- The admixture spreading mechanism needed to be modified or replaced with one suitable for radon seal application.
- The capacity of the asphalt emulsion pump had to be increased.
- The screed had to be modified to handle the high asphalt content mixture.

Continuous Portable Pug Mill and Paver. A continuous portable pug mill appeared to be well suited for mixing asphalt/aggregate admixture on-site. Seal application consisted of the following steps: 1) metering the asphalt emulsion and aggregate into the pug mill and mixing, 2) transferring the admixture to trucks, 3) transporting the admixture to a nearby standard asphalt laydown machine, and 4) applying the seal with the asphalt laydown machine.

Initial evaluations showed that the continuous portable pug mill was extremely attractive for mixing radon seal materials. The pug mill offers one

of the best aggregate coatings of central plant mixes and still maintains job-site control of the product quality (Caldwell 1975). Since the pug mill is located at the job site, the admixture can be rapidly transported to the paving site while it is still workable for paving operations. Pug mills are also 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.

A screening test near Eugene, Oregon, indicated that the pug mill merited further testing. Problems encountered in the screening test included poor calibration and some separation of the admix during the transfer to the paver. An asphalt emulsion containing a hydrocarbon solvent to maintain fluidity was used in these tests. The resulting admix containing local sand remained workable long enough to be paved. Asphalt emulsions without solvents were not available for this screening test. The asphalt emulsion/aggregate will have to be formulated to provide sufficient time for application before setting. A portable pug mill and paver were unsuccessfully field tested in 1980.

Transit Mixer. A transit mix truck capable of mixing and transporting concrete was considered for mixing 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 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 major disadvantage of the transit mixture is its low capacity ($\sim 8 \text{ m}^3$).

In a screening test in Eugene, Oregon, it was difficult to transfer the asphalt/aggregate admixture from the mixer to the paver. The mixture stuck to the side of the mixer and the transfer rate was quite slow. A transit mixer was unsuccessfully field tested in 1980.

Slurry Seal Machine. The asphalt/aggregate admixture used to seal radon is most similar to that used for slurry seals. However, the slurry seals are

normally only 3 to 6 mm thick and are used as pavement surface treatments. A slurry seal is not intended to increase the structural strength of the pavement.

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 merits of a slurry seal application system include:

- designed for higher asphalt contents
- inexpensive and uncomplicated operation
- provision for on-site asphalt mixing and laying
- minimal base preparation.

The disadvantages of the slurry seal system are:

- low production output rate due to batch operation
- lack of instrumentation for aggregate and emulsion feed rates
- difficulty in controlling depth of admix
- inadequate mixing provided by slurry seal pug mill.

A screening test in Sacramento, California, concluded that too many modifications would be required to overcome the disadvantages noted above. The primary difficulty was obtaining the required lift (5 to 6 cm) and its capacity was limited. The slurry seal was not field tested at Grand Junction, but it should be re-evaluated if thinner seals are considered.

Chip Seal. A chip seal has many of the advantages of sprayed-on seals and few of the disadvantages. The basic feature is the addition of aggregate for strength. A sprayed-on seal is initially applied over the tailings; then a calibrated depth of aggregate is applied by a chipper truck; and then another asphalt emulsion is sprayed on. This process continues until the required admix depth and/or asphalt content is obtained. The final mixture is compacted after it dries. The result is similar to macadam.

This process is fast and inexpensive and does not require specialized equipment or manpower. Unfortunately, the technique involves several problems. There would really be no mixing; a layered seal would result. Particle coating would vary significantly and, on the average, would be poor. Run-off would be hard to control, as would seal depth. However, because of the ease of application and the availability of the necessary equipment near the test site, this method was field tested in 1980.

Pneumatic Gun. 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 1969). If adapted 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 where they are applied at high velocity to the application surface (Reed 1977). 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. Because of the low capacity of these machines and anticipated problems with mixing and setting, the pneumatic gun was not field tested.

Drum Dryer. The drum dryer method of mixing asphalt and aggregate was also considered in the initial equipment review. 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. Discussion with manufacturers indicated that problems would be encountered in handling the fines in the aggregate and transferring the admixture to the paver. In addition, it appeared that this process would be quite expensive for on-site operation. The drum dryer was not field tested.

Central 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. The aggregate is dumped into a top-entering pug mill with two horizontal shafts, each with a number of paddles. The pug mill (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 are generally not used for mixing asphalt emulsions. Continuous mixers offer more control of the mixing time, which is critical for emulsions (10 to 15 s for CMS, 20 to 30 s for CSS), by adjusting the spray bar location (Huffman 1976). The central batch plant would also create transportation problems such as segregation of aggregate and asphalt, premature breaking, and stickiness, especially if the tailings site was in a remote area. The central batch plant was not field tested.

Blade Mixing and 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 that it was not worth pursuing. With the lack of control and the variability in mixing throughout the material, particle coating would probably be poor, run-off would be high, and problems of particle agglomeration would be encountered. This procedure was not field tested.

RADON FLUX FIELD MEASUREMENT SYSTEM

As part of the field studies, a radon flux measurement system was developed to evaluate the effectiveness of the radon barrier systems. The radon measurement system used during the field test was a pressure-balanced, flow-through system that uses activated carbon at ambient temperatures to collect the radon. A 0.93-m^2 area was sampled for periods from 1 to 12 h. The activated carbon was removed from the radon trap, and the collected radon was determined by counting the ^{214}Bi daughter product. A flow diagram of the system is shown in Figure 9. Development of the system is described in more detail by Freeman (1981).

Radon measurements were made before and after application of the asphalt radon barrier system. The procedure consisted of the following steps:

- The tent was 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.

FIGURE 9. Radon Diffusion Measurement System Used in Field Tests

- The flow rate and pressure drop through the system were adjusted to the desired values, and the radon flux was measured for a minimum of 4 h from the time the flow started through the activated carbon radon trap.
- After the measurement was taken, the activated carbon was placed in 2.5-cm x 15.2-cm diameter plastic Petri dishes and allowed to equilibrate for at least 4 h. The ^{214}Bi peak was then counted for 10 min using an intrinsic germanium diode or sodium iodide counting system.

The radon flux was determined from the area under the ^{214}Bi peak from the following equation:

$$J = \frac{\lambda^2 C}{(E)(A)(3.7 \times 10^{-2})(1 - e^{-\lambda t_1}) \left(e^{-\lambda(t_2 - t_1)} - e^{-\lambda(t_3 - t_1)} \right)}$$

where J = radon flux density, $\text{pCi m}^{-2}\text{s}^{-1}$
 C = net counts under ^{214}Bi peak
 λ = decay constant for ^{222}Rn , $2.097 \times 10^{-6} \text{ s}^{-1}$
 E = efficiency of counting system for ^{214}Bi , counts/
disintegration
 A = area of radon measurement tent, 0.929 m^2
 3.7×10^{-2} = conversion from d/s to pCi
 t_1 = measurement interval, s
 t_2 = time from start of measurement to start of gamma
counting, s
 t_3 = time from start of measurement to end of gamma
counting, s.

FIELD TEST RESULTS

Field tests were conducted in 1979, 1980, and 1981 at the Grand Junction, Colorado, tailings site. Grand Junction was selected as the site for the field tests because materials and equipment were readily available near the site and the tailings site was relatively level and required little site preparation. In addition, DOE facilities were available at the Grand Junction DOE office. The Grand Junction tailings site and the location of the three field tests are shown in Figure 10.

Six seal application methods were tested and two of them--the soil stabilizer and the cold mix paver--were tested twice. The results of these eight tests are summarized in Table 17.

1979 Field Test

Based on the evaluation of application techniques and equipment, the Bomag MPH 100 hydrostatic soil stabilizer (Figure 7) was chosen for the first field test. The primary objective was to test a stabilization procedure consisting of site preparation (contouring, watering, compacting), asphalt emulsion application using a hydrostatic stabilizer and compactor to form the seal, and protective overburden application. A $82.5 \times 82.5\text{-m}$ ($275 \times 275\text{-ft}$) site was prepared for the sealing test by removing a 5- to 15.2-cm (2- to 6-in.) cover of overburden that contained too much clay for an adequate seal. The site was then contoured for drainage, watered, and compacted.

FIGURE 10. Grand Junction Field Test Sites

TABLE 17. Summary of Field Test Results

	1979	1980	1980	1980
Application equipment	Soil stabilizer and distributor truck	Cold mix paver	Soil stabilizer	Continuous portable pug mill and paver
Type of seal	Admix plus sprayed-on seal; 8 to 13 wt% asphalt	Admix: 22 wt% asphalt	Layered admix; 20 to 24 wt% asphalt	Admix; 22 wt% asphalt
Aggregate	Tailings	Concrete sand	Tailings	Concrete sand
Asphalt emulsion	Armak cationic Redicote E-4868	Armak +73 mV (CMS)	Armak +18 mV, CSS and +18 mV (CSS-1 h)	Armak +73 mV (CMS) rubberized asphalt
Seal thickness, cm	15	8 to 18	8 to 11	Seal not applied
Area covered, m ²	6800	3400	800	0
Average radon flux reduction, %	76	99.7	96.5	NA
Average radon diffusion coefficient, cm ² /s	8x10 ⁻⁴	2x10 ⁻⁴	4x10 ⁻⁴	NA
Comments	Poor depth control, the sprayed-on seal provided most of the flux reduction. Over 99.9% reduction was achieved in some locations.	Good seal; some problems with slumping.	Multipass application; good seal.	Unsuccessful; admix setup in transfer truck.

TABLE 17. (Contd)

	1980	1980	1980	1981
Application equipment	Distributor truck	Distributor truck and chip spreader	Distributor truck	Cold mix paver
Type of seal	Sprayed on	Macadam, layered asphalt and aggregate; 22 wt% asphalt	Fog seal	Admix; 22 wt% asphalt
Aggregate	None	Concrete sand	None	Concrete sand
Asphalt emulsion	Styrene-butadiene rubberized asphalt	Armak +73 mV (CMS)	Armak +73 mV (CMS)	Armak +75 mV (CMS 2)
Seal thickness, cm	0.5 to 1.5	1.3 to 6	0.1 to 0.2	6
Area covered, m ²	120	270	~800	4900
Average radon flux reduction, %	99.3	99.6	95.7	99.6
Average radon diffusion coefficient, cm ² /s	6x10 ⁻⁶	NA	NA	7x10 ⁻⁵
Comments	Applied without difficulty; good seal.	Inconsistent application rate.	Fair to good seal, poor structural stability	Good seal; some problems with slumping and aggregate contamination.

Following some preliminary seal application equipment tests, a total of 4328 m² (1.07 acre) was sealed using the hydrostatic stabilizer (Figure 11). Cationic asphalt emulsion prepared with Armak Redicote E-4868 emulsifier was used for the admix seal. A few hours after the emulsion was applied, the tailings/emulsion mixture was compacted using a vibratory compactor to form an admixture seal. Several application rates were tried, including a double-pass application where ~8 wt% residual asphalt was applied on the first pass followed by an additional 8 wt% residual.

After most of the water evaporated, the admix was compacted 4 to 6 times using a vibratory compactor to form the admixture seal. A 3.2-l/m² (0.7-gal/yd²) spray coat seal was then applied to fill any microcracks that might have formed during compaction (Figure 12). An admix should be well-compacted to eliminate voids.

After the seal was compacted, core samples were taken to determine the thickness and asphalt content of the seal. The average thickness of the seal was 15 cm, almost twice what was planned. Because of this, the average asphalt

FIGURE 11. Soil Stabilizer in Operation During 1979 Field Test

FIGURE 12. Spray Coat Seal Being Applied to Asphalt Admix

content was only 11 wt% on a dry aggregate basis, about half of what was planned. Poor depth control with the hydrostatic stabilizer was the primary cause of these problems.

The compacted density of the seal was 1680 kg/m^2 (106 lb/ft^3), somewhat lower than expected. This lower density was primarily due to a poorly compacted base (tailings) and compaction before the seal had properly cured. The seal contained an average of 3.3 wt% water when it was compacted.

Radon flux from the Grand Junction tailings pile test site before applying the seal ranged from 12 to $2400 \text{ pCi m}^{-2}\text{s}^{-1}$. The average flux was $270 \text{ pCi m}^{-2}\text{s}^{-1}$, while the mean was $73 \text{ pCi m}^{-2}\text{s}^{-1}$ (Figure 13). The large flux range is due to the high radium content of the slimes compared with the sand. After the seal was applied, radon fluxes were reduced by 4.5% to 99.9%; the average flux reduction was 76% (Figure 14). Considering that the residual asphalt required for a total seal (18 to 20 wt%) was not obtained, the test was still a success. In most cases, areas covered with sprayed-on seal were adequately sealed. Areas where the seal failed indicated an average 104% increase in flux, which was caused by the lateral diffusion of radon to a crack or breach in the seal; however, this flux increase would not have a significant effect on overall radon concentration above the seal.

FIGURE 13. Radon Flux Measurements from 1979 Field Test Before Seal Application

FIGURE 14. Radon Flux Measurements from 1979 Field Test After Seal Application

After compaction, about two-thirds of the seal was covered with ~20 to 30 cm (8 to 12 in.) of overburden. The overburden protected the site from mechanical abuse and weathering. The remainder of the seal was left uncovered for comparison. In part of the area covered with overburden, a herbicide (Treflan®) was sprayed after 10 to 15 cm of the overburden had been applied. The rest of the overburden was then applied.

The results of the 1979 field test indicated that an effective asphalt radon barrier system could be constructed, but additional application techniques should be investigated. Details of this field test are included in the 1979 annual report (Hartley et al. 1980).

1980 Field Test

Four techniques for applying an admix seal were field tested in 1980: 1) a cold mix paver, 2) a continuous pug mill and paver, 3) a concrete truck and paver, and 4) a soil stabilizer. The first three were selected on the basis of screening tests conducted early in 1980. A modified application technique was used with the soil stabilizer, which had been previously field tested in 1979. In addition, two sprayed-on seals were tested: 1) a multi-layer sand seal, similar to macadam, applied with an asphalt distributor truck and a chip spreader, and 2) a rubberized asphalt seal applied with a distributor truck.

The field test, conducted in August 1980, consisted of site preparation and characterization, seal application, and overburden and biobarrier application. A 76.2 x 76.2-m (250 x 250-ft) site was prepared for the application tests by removing a 5- to 15.2-cm (2- to 6-in.) cover of overburden and then contouring the site for drainage. The test area was watered and compacted to attain maximum density. A 5 wt% residual asphalt was applied to a 10-cm (4-in.) depth in the tailings with a soil stabilizer and then compacted to maintain density and strength. This procedure provided a base for the paving equipment.

Based on ease of application, the cold mix paver (Figure 15) showed the most promise in applying an admix seal consisting of concrete sand and a +73 mV

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FIGURE 15. Cold Mix Paver in Operation During 1980 Field Test

CMS asphalt emulsion. Seal depths of 7.6 to 15.2 cm (3 to 6 in.) were applied in 3- to 3.7-m widths to cover a total area of 3440 m² (0.85 acre). The residual asphalt content of the seal averaged 22 wt%.

An additional asphalt pump was added to the cold mix paver to obtain the asphalt content required. The high asphalt content of the admix made it more fluid than the cold mix paver is designed for, and the admix had a tendency to slump outside the spreading unit. The 5 wt% asphalt-stabilized base was not sufficient to support the cold mix paver. About 5 to 8 cm of road-base gravel was spread over the tailings and compacted to provide a suitable base for the paver.

The soil stabilizer mixed 18 mV CSS asphalt emulsion directly with the tailings to form an admix ~10.6 cm (4 in.) deep that covered ~800 m² (0.2 acres). The average asphalt content of the seal was 22 wt%. A multipass technique was used, consisting of the following steps:

- Step 1 - mix water and tailings with soil stabilizer
- Step 2 - apply ~7 wt% asphalt to tailings
- Step 3 - mix asphalt and tailings with soil stabilizer
- Step 4 - repeat Steps 2 and 3 until a 22 wt% asphalt/tailings admixture is obtained.

The multipass technique worked reasonably well, although some problems with depth control and mixing were encountered.

The continuous pug mill (see Figure 16) was able to successfully mix the CMS emulsion with concrete sand to form a good admix. Three asphalt emulsions were tested with this technique: 1) +73 mV CMS, 2) +50 mV CSS-1h/CMS mix, and 3) +18 mV CSS-1h. Problems were encountered in transporting the admix to the paver. The admix settled in the dump truck and would not flow into the paver. Preliminary tests with the concrete truck mixer were unsuccessful because of poor mix control; therefore, this technique was not tested further.

The chip seal test (Figure 17) was a partial success. Problems included inconsistent application rate and poor penetration of the asphalt emulsion into the concrete sand. The result was a layered seal that was a good radon barrier but did not have the mechanical strength of a well-mixed admix seal.

After all the admixes were applied, they were allowed to cure for several days before being rolled with a vibratory and static steel roller to form the final 7.6-cm (3-in.) seal.

In addition to the various asphalt emulsion seals, a hot rubberized asphalt seal was applied to an 167 m^2 (200 yd^2) area of tailings. A 0.5- to 1.5-cm thick seal was applied using a distributor truck (see Figure 18). Since the material was a homogeneous asphalt rubber phase instead of the usual two-phase (ground-tire asphalt) mixture, it showed promise as a radon seal. After all seal application tests were completed, the test area was sampled and radon flux was measured. A biological barrier consisting of a herbicide (Treflan) and an animal intrusion barrier (rock) was applied to part of the test area followed by overburden application. Revegetation of the test site was then initiated using both native and induced species. A view of the test site three years after planting is shown in Figure 19.

Radon fluxes from the 1980 Grand Junction tailings test site before seal application (see Figure 20) ranged from 86 to $1149 \text{ pCi m}^{-2}\text{s}^{-1}$. The average flux was $409.5 \text{ pCi m}^{-2}\text{s}^{-1}$. The large range in flux was due to the high radium content present in some areas of the test site.

FIGURE 16. Continuous Portable Pug Mill Loading Asphalt Admix into Truck

FIGURE 17. Chip Spreader Applying Sand Over Initial Coat of Asphalt Emulsion

FIGURE 18. Applying Hot Rubberized Asphalt

FIGURE 19. Vegetation Planted on 1980 Test Site (photo taken in 1983)

Radon fluxes after the seals had been applied ranged from 0 to 344.5 $\text{pCi m}^{-2}\text{s}^{-1}$ as shown in Figure 21. The average flux was 10.0 $\text{pCi m}^{-2}\text{s}^{-1}$. The most successful seal technique was the cold mix paver. Fluxes measured over this area ($\sim 76.2 \times 51.8 \text{ m}$) ranged from 0 to 0.6 $\text{pCi m}^{-2}\text{s}^{-1}$ with an average of 0.2 $\text{pCi m}^{-2}\text{s}^{-1}$, which corresponds to an average flux reduction greater than 99.9%. Flux reductions for all the application techniques are shown in Table 18. The cold mix paver, the chip seal, and the hot rubberized asphalt all reduced the radon flux by at least 99%.

FIGURE 20. Radon Flux Measurements Taken on 1980 Test Plot Before Cover Application

FIGURE 21. Radon Flux Measurement Taken on 1980 Test Plot After Cover Application

TABLE 18. After-Seal Radon Flux in Each Test Area

Application Technique	Flux Range, $\text{pCi m}^{-2}\text{s}^{-1}$	Average Flux Reduction, %
Soil stabilizer	0.6 to 178	96.5
Cold mix paver	0 to 0.6	99.9
Chip seal (macadam)	1.4 to 4.3	99.6
Fog seal	0.3 to 344	90.1
Hot rubberized asphalt	0.5 to 12.9	99.3

Of these three, the cold mix paver seal was the only one with sufficient mechanical strength. Based on ease of application and the effectiveness of the seal, the cold mix paver was the best application technique tested. Details of the 1980 field test are included in the 1980 annual report (Hartley et al. 1981a).

1981 Field Test

The purpose of the 1981 field test was to provide data for evaluating the technical and economic feasibility of using the cold mix paver for large-scale sealing of uranium mill tailings with asphalt/aggregate admixtures. The cold mix paver was modified to prevent some of the problems encountered in the 1980 field test. The costs incurred during the 1981 field test were compiled to provide a basis for estimating the cost of large-scale application.

A 22 wt% residual asphalt aggregate admix seal was applied ~12 cm thick (uncompacted) over a 45.6 x 76 m area (0.86 acres) with a cold mix paver. A +73 mV CMS asphalt emulsion containing 63 wt% asphalt was mixed with concrete sand to form the admix.

To prepare the site for seal application, the top 10 to 25 cm of cover material was removed and the site was surveyed and contoured. About 10 cm of 1.9-cm (3/4-in.) gravel road base was spread, watered, and compacted to provide a stable base for seal application (Figure 22).

The cold mix paver illustrated in Figure 23 was used to apply the seal. A distributor truck pumped the asphalt emulsion into the asphalt tank on the paver and dump trucks loaded the concrete sand into the paver hopper. The cold

FIGURE 22. Compacting Gravel Road Base Before Seal Application

FIGURE 23. Cold Mix Paver in Operation During 1981 Field Test

mix paver was modified before the application to allow smoother operation with the high residual asphalt content of the admix. The aggregate feed belt speed was reduced, and the asphalt emulsion pumping capacity was increased. Approximately 2318 kg/min of sand and 900 l/min of emulsion were mixed in the pug mill to produce an admix seal with 22 wt% residual asphalt (22 kg/100 kg of dry aggregate). Ten strips, each ~4.6 m wide, were required to cover the test plot. Each 4.6 x 76 m pass required a little over 15 min. Overall, 145,000 l of asphalt emulsion were applied on the test area.

Six weeks after application, the seal was compacted with a vibratory roller (Figure 24) to a thickness of ~6 cm. Overburden was spread over the test area to a depth of 0.6 m (Figure 25).

An additional 27,200 l of emulsion was used to apply an admix seal on a 7% slope next to the main test plot (see Figure 26). No problems were encountered in paving up the slope. Visually the seal appeared as good or better than that applied on the relatively flat test plot.

After the seal was applied, 16 samples were taken from various locations to determine the asphalt content, thickness, and moisture content of the seals.

FIGURE 24. Compacting the Asphalt Admix Seal

FIGURE 25. Applying Protective Overburden on Asphalt Admix

FIGURE 26. Cold Mix Paver Applying a Seal on a 7% Slope

Radon flux over the test area before seal application ranged from 133 to 1198 pCi m⁻²s⁻¹ with an average of 556 pCi m⁻²s⁻¹. The flux measurements are shown in Figure 27. The fluxes after seal application ranged from 0.0 to

FIGURE 28. Radon Flux Measurements on 1981 Test Plot One Year After Seal Application (July 1982)

26.5 $\text{pCi m}^{-2}\text{s}^{-1}$ with an average of 1.5 $\text{pCi m}^{-2}\text{s}^{-1}$ (Figure 28). The average flux reduction was 99%. The higher flux values resulted from leaks in the seal, caused by the accidental addition of some clay during admix aggregate loading operations. More details on the 1981 field test are provided by Hartley et al. (1983) and Baker et al. (1982).

Field Test Monitoring

The three field test sites have been monitored periodically since 1981. Radon fluxes for five of the test plots are shown in Table 19. Except where noted in the table, the radon fluxes measured in July 1983 are essentially the same as those measured after the seals were applied, indicating that there has been no loss of effectiveness in the 2 to 4 years the seals have been in place. In 1983, core samples were taken from the 1979, 1980, and 1981 test plots. There were no obvious signs of degradation. All of the samples except the rubberized asphalt were ~10 cm (4 in.) in diameter.

TABLE 19. Radon Flux Versus Time for Various Asphalt Seals

Seal Type	Average Radon Flux, $\text{pCi m}^{-2} \text{s}^{-1}$					
	Before Application	Immediately After Application	February 1982	July 1982	October 1982	June 1983
Cold mix paver 1981	556	4.1 ^(a)	0.4	1.5	0.9	0.8
Cold mix paver 1980	294	0.3	1.0	0.3	-	0.5
Hot rubberized asphalt 1980	882	6.0	-	-	-	5.4
Soil stabilizer (in situ) 1980	606	29.8	-	-	-	29.5
Soil stabilizer (in situ) 1979	270	65.4	-	-	-	15.4 ^(b)
Sprayed-on seal 1980	468	46.5				
Chip seal 1980	821	2.1				

(a) Totally different locations were used for the June 1983 measurements. This shows the lack of consistency for this seal.

(b) This measurement was taken before the protective overburden was applied. Flux measurements near the edge were high, apparently from lateral diffusion, but dropped dramatically after the overburden was applied.

The 1979 soil stabilizer sample (Figure 29a) was only ~4 cm thick, and the asphalt and aggregate were not well mixed. Figure 29 also shows the top spray coat on the sample. Figure 29b shows a much better soil stabilizer sample taken from the 1980 test plot.

An example of the layered chip seal is shown in Figure 29c. A sample of hot rubberized asphalt is shown in Figure 30a. This rubberized asphalt is not an admix seal, but it has held up well for three years of service. The sample was about 1½ cm thick, was quite flexible and showed no sign of embrittlement.

Samples of the seals applied with a cold mix paver in 1980 and 1981 are shown in Figures 30b and 30c. These seals were both 6 to 8 cm thick, and the asphalt and aggregate appeared well mixed. The cold mix paver samples were quite hard at room temperature but still "cold flowed" a little when allowed to stand unconfined. Both of these properties are desirable for a radon barrier system. Radon diffusion measurements were made on some of these samples (see Table 17).

a) Soil Stabilizer
1979 Field Test

b) Soil Stabilizer
1980 Field Test

c) Chip Seal
1980 Field Test

FIGURE 29. Specimens Taken from 1979 and 1980 Field Test Plots in July 1983

a) Hot Rubberized Asphalt
1980 Field Test

b) Cold Mix Paver
1980 Field Test

c) Cold Mix Paver
1981 Field Test

FIGURE 30. Specimens Taken from 1980 and 1981 Field Test Plots in July 1983

CONCLUSIONS FROM FIELD TESTS

The radon fluxes achieved with seven field-tested asphalt seals are shown in Figure 31. The cold mix paver seal is well below the EPA standard of $20 \text{ pCi m}^{-2}\text{s}^{-1}$. The hot rubberized asphalt also easily meets the flux standard, and could be further improved by a more consistent application. The chip seal also easily meets the standard. It appears that a seal applied in situ with the soil stabilizer, if applied consistently, could also meet the standard. The same holds true for the sprayed-on seal. In general, all of the different

FIGURE 31. Effectiveness of Various Field-Tested Asphalt Seals

types of asphalt seals, if properly applied, can meet the EPA radon flux standard, so that the choice between the different types of seals should be based on other factors.

Table 20 lists the relative merits of each type of asphalt system. The cover systems are ranked in relation to each other, with (++) indicating the most effective, followed by (+), and (-) as the least desirable or effective. Overall, the cold mix paver system is best. The seal can be applied easily and consistently and its long-term stability appears to be excellent (see Long-Term Stability Studies). The hot rubberized asphalt could be significantly less expensive (because it is a thinner seal); however, there remains the question of its long-term stability. The samples removed from the test plot in 1983 were all in excellent condition and had retained their flexibility.

The other three systems shown in the table all have drawbacks that make them less promising. Applying an in situ seal with the soil stabilizer was difficult and inconsistent. The long-term stability of the sprayed-on and chip seals is still questionable.

TABLE 20. Relative Merits of Various Asphalt Seals

Criteria	Type of Seal				
	Cold Mix Paver	Hot Rubberized Asphalt	Soil Stabilizer (in situ)	Sprayed-on	Chip
Ease of application ^(a)	+	++	-	++	-
Consistency of application ^(b)	++	+	-	-	-
Efficiency of seal ^(c)	+	+	+	+	+
Overall effectiveness ^(d)	++	+	-	-	+
Long-term stability ^(e)	++	+	+	-	+
Cost ^(e)	-	+	-	++	+

(a) Based on field-test experience with the various application equipment.

(b) Based on field-test experience and the range of radon flux reductions achieved on each test plot.

(c) Based on diffusion coefficients and the radon flux reduction achieved by a good seal.

(d) Based on the overall radon flux reduction achieved (a combination of consistency and efficiency).

(e) Calculated for the cold mix paver seal; the other seal types are ranked in relation to it.

LONG-TERM STABILITY STUDIES

Seal stability and the effective lifetime of a radon barrier system are important concerns. Experience with this type of asphalt/aggregate system is minimal. However, the several decades of experience with asphalt pavements have served as a guide in assessing the critical areas of asphalt degradation in a 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 1979). Poor mix control results in weak asphalt/aggregate bonding; asphalt separation from the aggregate (stripping) can also occur (Asphalt Institute 1979). 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 residual water content of the pavement; 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 viscosity increase (embrittlement) that occurs gradually over time, and 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 the attack. Water leaching of asphaltic components from pavements depends partly on the extent of asphalt fatigue (Kleinschmidt and Snoke 1959). Many factors that adversely affect road performance are minimized

in the asphalt emulsion/aggregate radon barrier system. However, there are several means by which degradation of asphalt in the radon barrier system may occur. For this discussion, we have divided these into chemical degradation and physical degradation.

CHEMICAL DEGRADATION

Based on the preliminary literature investigation of asphalt degradation, it appears that autooxidation, leaching, and microbial attack are the most likely causes of chemical degradation in the asphalt cover system. Laboratory studies and additional literature review did not reveal any serious problems due to chemical degradation.

Autooxidation

Autooxidation 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 because most autooxidations are accelerated by light or traces of catalysts or decelerated by antioxidants.

The autooxidation of organic compounds is considered a free radical reaction and has been extensively reviewed (Kochi 1973; March 1977). Important factors that determine autooxidation susceptibility are the free radical initiation rate and the efficiency of free radical chain propagation. Autooxidation 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, which 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 autooxidation products, and autooxidation can increase aromaticity and molecular weight. In asphalt, cross-linking and hydrogen-bonding can produce high molecular weight asphaltenes.

Several factors affect the autooxidation 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 autooxidation is a gas/solid reaction. The initial oxidative weathering of asphalt causes an asphaltene skin to form on the surface. This protective skin slows oxygen transport into the bulk asphalt, thus retarding the autooxidation 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 is 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 autooxidation, should decrease 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 autooxidative asphalt fatigue. Normal asphalt road pavements have very high internal surface area due to the voids content, and the asphalt in these pavements forms a thin film about the aggregate because of the low overall asphalt content. These two factors make the interior of the asphalt pavement very susceptible to autooxidative 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 autooxidation should occur primarily at the admix surface. The formation of an outer asphaltene skin on the admix limits oxygen diffusion to the seal interior, further inhibiting autooxidative asphalt failure. Asphaltene skin erosion should be prevented by the protective overburden, which also protects the seal from sunlight and may reduce oxygen and hydroxyl radical exposure to the asphalt, thus limiting the initiation of autooxidation reactions. Furthermore, the asphalt is not exposed to nitrogen oxide and other internal engine combustion products that can cause autooxidation (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 autooxidation reaction rates. The asphalt emulsion/aggregate

admix coupled with a protective overburden layer is a different physical system from asphalt road pavements; seal durability predictions based solely on road experience are tenuous.

Laser-Raman spectroscopy was used to determine the amount of oxygen uptake by different asphalt samples. Six asphalt samples were sealed in ampoules under air: three admix samples from the 1981 field test, an emulsion sample from the 1981 field test, an admix sample from the 1980 field test, and a sample of asphalt sidewalk (1946) at Camp Hanford were included. The results after 40 days of exposure are shown in Table 21. The amount of oxygen absorbed was about the same for all four 1981 field test samples. The 1980 field test sample absorbed the largest amount of oxygen; and the 1946 Camp Hanford sidewalk, the least. The amount of oxygen absorbed was the same order of magnitude for all six samples.

These results indicate that some oxygen was absorbed by the field test samples; however, these results do not indicate actual chemical oxidation of the asphalt. In addition, the quantity of oxygen absorbed would be less in terms of volume per weight of asphalt for thicker admix seals as compared with the small ampoule sample.

TABLE 21. Laser-Raman Spectroscopy of Air Components
Over Asphalt in Sealed Ampoules

<u>Asphalt Type</u>	<u>O₂ Absorption^(a)</u>
1980 field test seal (collected 4/81)	Fast
1981 field test seal (collected 2 days after laydown)	Moderate
1981 emulsion (from truck at site, not exposed to light)	Moderate
1981 field test seal (collected 10/81)	Moderate
1981 field test seal (collected 10/81)	Moderate
1946 asphalt (Camp Hanford sidewalk)	Slow

(a) Fast indicates $>2 \text{ cm}^3 \text{ O}_2/\text{g}$ asphalt; moderate indicates $0.75 \text{ to } 1.0 \text{ cm}^3 \text{ O}_2/\text{g}$ asphalt; slow indicates $<0.75 \text{ cm}^3 \text{ O}_2/\text{g}$ asphalt. All values compared at 40 days exposure in sealed ampoules.

A differential infrared spectroscopy technique was used to look at actual oxidation products in asphalt samples. The analytical procedure was adapted from Peterson and Plancher (1981). One sample from both the 1980 and 1981 field test was analyzed in July 1981 and July 1982 (Table 22). In addition, the 1946 sidewalk from Camp Hanford was used as a reference well-oxidated asphalt.

The oxidation of the two field test seal samples was extremely low for the first 1 to 2 years of oxygen exposure. The 36-year-old Camp Hanford admix contained 4% asphalt and a great amount of void space to facilitate oxidation. The seal admix samples contained 18% asphalt and presented minimal surface area exposure. The ketone content after 2 years (7/80 sample) was 3×10^{-4} moles/g asphalt, while that of the 36-year-old sample was 2.4×10^{-2} moles/g asphalt. At such a rate, it would take 150 years to reach the sidewalk oxidation content. However, these values totally ignore kinetics, oxygen diffusion through thick asphalt seals, and other oxidation mechanisms. The results do indicate that the oxidation of the seal admix samples was quite slow within the initial 1 to 2-year period.

Leaching

In the natural weathering of asphalt, water leaches out oxidized constituents and promotes erosion but apparently does not contribute significantly to age hardening (Martin 1964). Oxidized asphalt films were immersed in water and their viscosities were compared with control samples. No significant difference was noted, indicating that water had little effect on hardening.

TABLE 22. Oxidation Products in Asphalt as Determined by Differential Infrared Spectroscopy (moles/g asphalt)

Asphalt Type	Analyzed July 1981		Analyzed July 1982	
	Ketones	Acid/Anhydrides	Ketones	Acid/Anhydrides
1980 Grand Junction field test (sampled 4/81)	0	<0.00004	0.0003	0.00004
1981 Grand Junction field test (sampled 7/81)	0	<0.00004	0	0.00016
1946 asphalt (Camp Hanford sidewalk)	0.024	0.0046	---	-----

Other work has shown that the water-soluble components of asphalt are primarily oxidation products from the lower molecular weight fraction of the asphalt.

Preliminary laboratory tests showed that proper curing is necessary to prevent seal failure due to leaching and that admix seals were more resistant to leaching than sprayed-on seals. Eight asphalt admix and sprayed-on seals were leached for 30 months in laboratory experiments. Polycarbonate cylindrical cells (see Figure 32) were prepared so that aqueous leaching could be investigated in the laboratory. Asphalt seals were buried in acid-washed sand in the 15-cm diameter cells to eliminate photocatalytic oxidation. Half of the seals were exposed to distilled water; the other half, to a brine solution containing 21 salts at pH 1.6. The brine solution simulates the composition of the slimes fraction of the Grand Junction tailings. The flow rate of the water and brine over the seals was 1.4 l/day. Two cells were dismantled every 6 months to examine both the leachate and the admix seal (Figure 33). The asphalt was weighed and the leachate was extracted with dichloromethane to remove organic materials. The results are presented in Table 23.

The amount of asphalt extracted with both the distilled water and the brine did not increase steadily with time as would be expected; however, a different sample was examined every six months, which undoubtedly accounts for much of the variability. The asphalt weight loss for the brine samples was about twice as much as for the distilled water samples, but in both cases was quite low. No degradation of any of the admix seals was noted. Some grooves caused by solution run-off were detected in some of the seals. The weight loss for the sprayed-on seals was similar to that of the admix seals.

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. Soils contaminated with petroleum have been reclaimed by inoculating the soil with oil-digesting bacteria (Odu 1977a, b). However, asphalt is less susceptible to microbial degradation than oil, probably because high-molecular-weight

FIGURE 32. Leaching Test Apparatus

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 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.

During the testing of canal liners under optimal growth conditions for bacteria, only about a 1-mil (0.025-mm) thickness of asphalt was affected in 3 years (Jones 1965). It appears that even under optimal conditions microbial attack on asphalt is slow and would be reduced by design of the radon barrier system.

FIGURE 33. Leaching Test Cell and Specimen

TABLE 23. Leaching of Asphalt Samples with Water and Brine Solutions

Exposure Time, months	wt% Asphalt Lost	
	Distilled Water	Brine
6	0.009	0.053
12	0.015	0.026
18	0.031	0.058
24	0.017	0.033
30	0.005	0.034

PHYSICAL DEGRADATION

The asphalt/aggregate admix system was selected over poured-on asphalt seals because of its apparent superior physical strength. Strength characteristics were determined by the University of New Mexico (UNM). In addition, PNL

investigated the effect of differential settlement of the tailings pile on the seal, the effect of freeze/thaw cycles, and the possibility of plant or animal intrusion into the seal. None of these appears to present a serious threat to the integrity of the seal system.

Physical Properties of Asphalt Admix Seals

The physical properties of asphalt admix seals generally depend on stress conditions and temperature. The two components of asphalt admixes have completely different characteristics. The major portion of the mix is made up of the mineral aggregate, which is mainly elastic. The asphalt portion, however, behaves as a viscous liquid at high temperatures or under sustained loads and as an elastic material at low temperatures or when subjected to impact load. Hence, asphalt admixes have both elastic and plastic properties.

The stability or load-carrying capacity of asphalt is determined by its strength characteristics. The strength of asphalt admix seals has been quantified using several parameters and tests: creep, modulus values, and triaxial shear strength. The samples used for testing were collected from the 1981 asphalt emulsion test site in Grand Junction, Colorado.

A summary of the UNM triaxial compression tests is presented in Figures 34 and 35. All cores were 3.8 cm (1.5 in.) in diameter and trimmed to 7.6 cm (3 in.) lengths. A strain rate of 1% per minute was used for all tests. Typically, the failure envelope is curved, based on total stresses. Thus, the angle of internal friction (ϕ) and cohesion (C) are often only for higher confining stresses. UNM tests provided strength parameters of $C = 1.2$ to 111.5 psi and $\phi = 4^\circ$ to 16° at the respective test temperatures.

Temperature has a significant effect on the shear strength of the asphalt admix material, as noted by the strength parameters. Shear strengths ranged from 1 to 4 psi at 75°F (24°C), 25 to 35 psi at 50°F (10°C), and 145 to 170 psi at 25°F (-4°C). A two orders of magnitude change in shear strength was observed over a temperature span of 50°F (28°C).

Another important property of an asphalt admix seal is flexibility. Flexibility allows the seal to conform to slight irregularities in the subgrade and to adjust to small differential settlements that inevitably occur after the completion of the cover.

FIGURE 34. Effective Stress Envelope for Asphalt Admix Seal at 75°F (24°C)(a)

FIGURE 35. Effective Stress Envelope for Asphalt Admix Seal at 25°F (-4°C)(a)

(a) Information provided by D. J. Hamberg, University of New Mexico, Albuquerque, New Mexico, August 19, 1981.

Increased asphalt content helps to satisfy the preceding design requirements. After a certain point, however, an increase in asphalt content results in a decrease in stability. The asphalt admix seal, when cured, contains ~22 wt% asphalt and less than 1 wt% water.

To investigate the ability of the admix seals to deform, third-point bending tests were performed at PNL on samples collected over a number of different surfaces. These samples represent the central portion of a pass by the asphalt cold mix paver, joint planes, and a repaired area of the seal.

Figures 36 and 37 show the change in creep rate of the asphalt admix seal with changes in applied load and temperature. The temperature and applied load ranges were selected to simulate Grand Junction field-test conditions where the seal is covered by 0.6 to 0.76 m of overburden.

During the later loading cycles, signs of strain hardening are evident. This effect is most apparent in Figure 36 where Cycles 3 and 4 have substantially lower creep rates. The dramatic effect of temperature is shown in Figure 36, where the creep rate at 25°C (77°F) is an order of magnitude greater than at 60°C (43°F).

The percent elongation (deflection) versus time for the asphalt admix seal under load is shown in Figure 38. Percent elongation at yielding and failure is given in Table 24, where yielding is defined as the point where the deflection versus time curve changed from steady state to accelerating. Failure was defined as the point where the sample could no longer support itself.

Flexural strength tests were performed at UNM to determine the ultimate bending moment that the asphalt beam could resist at varying temperatures. The stress in the extreme fibers, based on the elastic flexure formula for the experimentally determined ultimate bending moment, is called the rupture modulus of the material in bending. Modulus of rupture values for the asphaltic admix seal, at various temperatures, are given in Table 24 and shown graphically in Figure 39. A procedure similar to ASTM C78-75, "Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," was used with a constant strain rate of 0.32 in./min for all tests. This strain rate is not in accordance with ASTM C78; however, it was necessary to overcome creep effects in the soft asphalt admix samples.

FIGURE 36. Effect of Applied Load on Creep Rate

FIGURE 37. Creep Rate as a Function of Applied Load and Temperature

FIGURE 38. Percent Elongation as a Function of Time

TABLE 24. Percent Elongation at Yield and Failure

Sample	Temperature, °C	% Elongation Yield	% Elongation Failure	Thickness of Slab, in.	Sample Field Location
1	0	% elongation = 0.3% after 13 days, no yielding; load was 277 lb		2.5	Center of pass
2	25	4.1	26.4; did not fail	2.5	From patch area
3	28	0.8	13.6	3.25	Joint runs through sample
4	6	1.8	5.7	2.0	Center of pass
5	6	1.8	20.4	2.5	Joint runs through sample

*NONVALID TESTS ACCORDING TO ASTM C78-NOT USED FOR REGRESSION FIT

FIGURE 39. Modulus of Rupture as a Function of Temperature^(a)

Differential Settlement

The asphalt/aggregate admix must be able to withstand, without cracking, long-term loading stresses caused by differential settlement that can occur in the uranium mill tailings pile. In addition, the asphalt admix seal must also be resilient under short-term loading caused by shrinkage and/or swelling of the tailings pile.

(a) Information provided by D. J. Hamberg, University of New Mexico, Albuquerque, New Mexico, August 19, 1981.

Differential settlement will occur on the surface of piles due to drainage and due to stress increase resulting from cover placement. The settlement due to drainage results from an increase in the stress state variables caused by an increase in the capillary tension or suction in the water. Thus, settlement of the tailings pile is due to increases in the total stress applied by the weight of the cover and increases in capillary tension as consolidation drainage takes place.

The general magnitude of settlement that could be expected due to placement of a 2.5-ft (76-cm) thick cover and subsequent drainage of the tailings was calculated. The computations, summarized in Table 25, indicate that settlements of the magnitude of 1.94 in. (4.92 cm) and 3.99 in. (10.13 cm) could occur for tailings zones composed of 60% sands/40% slimes and 100% slimes, respectively. For the slime zones, settlements may be greater from drainage than those resulting from the increase in total stress due to the weight of the cover. In addition, settlement of the slimes is expected to take place over several years, whereas settlement of the sands is expected to occur relatively rapidly.

Relatively definite boundaries between sand and slime zones may result from deposition of tailings into pools. Because of the different rate of settlement between the sands and slimes, differential settlements may take place over relatively short distances. Hence, assuming the maximum predicted settlement of the 60% sands/40% slimes, it is important to know the asphalt admix seal's minimum manageable span and the allowable elongation that results. Figure 40 is a plot of percent elongation versus span, assuming a total deflection of 1.94 in. (4.92 cm) at the center. Assuming the worst case, the minimum span length that the asphalt admix seal could withstand without failing is 1.1 ft (0.34 m). The seal would presumably rupture if differential settlement

TABLE 25. Expected Settlement of Tailings Pile

Settlement	60% Sands/40% Slimes	100% Slimes
Cover load	1.36 in. (3.45 cm)	1.88 in. (4.77 cm)
Drainage	0.58 in. (1.47 cm)	2.11 in. (5.36 cm)
Total	1.94 in. (4.92 cm)	3.99 in. (10.13 cm)

FIGURE 40. Elongation Versus Span for an Asphalt Admix Seal

resulted in a span less than this. None of the samples tested would reach their yield point at spans greater than 1.97 ft (0.6 m). The results neglect membrane stresses and possible scaling effects (Gates 1983).

Freeze/Thaw Cycling

The force exerted by water freezing and expanding is the primary cause of highway pavement deterioration in the northern United States. The resulting deterioration is known as "stripping." An asphalt radon barrier system can be expected to be exposed to cyclic freeze/thaw conditions during service. A literature search revealed that two cyclic freeze/thaw tests were in use. A test developed at the DOE Laramie Energy Technology center is recognized as the most severe test. Essentially no petroleum-based road asphalts remain integral beyond a few cycles unless an antistripping agent is added. The procedure is described in detail by Plancher et al. (1980). The modified procedure used to test asphalt emulsion radon barrier systems was intended to simulate field conditions. It consisted of the following steps:

- The asphalt/aggregate admixture was placed in an oven at 50°C and allowed to dehydrate for 3 to 5 days.
- The dehydrated sample was placed in an ambient temperature mold and compacted at 6200 lb for 20 min.
- The specimen was extruded and cured for 3 days at ambient temperature.
- The specimen was placed on a stress pedestal and then frozen and thawed as described by Plancher, except that the samples were thawed at 38°C instead of 60°C.

At 54°C, the samples all failed due to cold flow of the specimen mounted on the pedestal (Figure 41). Cold flow results from the high asphalt content and the high exposure temperature with 0.6 to 1 m of overburden. The upper seal temperature is not likely to exceed 32°C (90°F). After the initial testing, all samples were thawed at 38°C (100°F) as part of the prescribed procedure.

The cyclic freeze thaw tests are summarized in Table 26. The following conclusions are based on the test data:

- The Plancher test is not directly applicable to this type of specimen, but the specimen preparation and freeze/thaw exposure conditions can be modified to closely simulate field conditions. With these modifications, the Plancher test simulates field seal specimens and provides very severe exposure conditions.
- All specimen failures were caused by specimen slumping. No specimen failure was related to freezing. The high asphalt content required for a radon gas-tight seal does not allow water permeation and subsequent freeze damage.
- The specimens fabricated from emulsions containing the higher viscosity asphalts (Samples 19-24) remained unchanged in 20 freeze/thaw cycles.

FIGURE 41. Pedestal Used for Thawing Samples in Freeze/Thaw Tests

TABLE 26. Summary of Cyclic Freeze/Thaw Test Data

Test Number	Emulsion Type	Asphalt Penetration	wt% Asphalt	Number of Cycles ^(a)
16-18,25-28	Armak +78 mV	120/150	20.1	12,6F,12,1F,19,14F,9F
19-21	Armak +78 mV	85/100	20.1	19, 19, 19
22-24	Armak +78 mV	60/70	20.1	19, 19, 19
32-33	U.S. Oil CMS	--	20.4	1F, 1F
34-35	Chevron CMS	--	20.4	1F, 1F
54-56	Rubberized asphalt	--	20.4	12, 12, 12
57-59	Rubberized asphalt	--	15.0	12 12, 12
60-62	Rubberized asphalt	--	10.2	1F, 1F, 1F
63-65	Asphalt cement	85/100	20.2	7, 7, 7
66-68	Asphalt cement	85/100	15.0	7, 7, 7
69-71	Asphalt cement	85/100	10.2	7F, 7F, 7F
86-88	Armak +78 mV (incompletely dried)	60/70	20.7	1F, 1F, 1F

(a) F indicates failure; all failures were due to slumping (cold flow), not freezing.

- Specimens fabricated from emulsions containing solvents (Samples 32-35) all failed on the initial thaw cycle due to excessive slumping.
- The higher concentration asphalt-rubber latex specimens (Samples 54-59) did not crack in 12 cycles; however, all assumed a tan color and expanded in progressive cycles. The low concentration asphalt-rubber latex specimens (Samples 60-62) slumped or disintegrated on the initial thaw cycle.
- Higher asphalt cement specimens (Samples 63-68) remained intact as far as the test progressed. Lower concentrations (Samples 69-71) slumped or disintegrated on the initial thaw cycle.
- Incompletely dried samples (Samples 80-88) simulated premature field compaction; all failed on the initial thaw cycle due to excessive slumping.

Plant and Animal Intrusion

This study was undertaken to determine the magnitude of plant and animal intrusion of radon barrier systems (including asphalt covers) and to test physical and chemical barriers to prevent intrusion.

Asphalt admix seals and poured-on asphalt emulsion seals were tested in lysimeters made from PVC pipe 15 cm in diameter and 1 m long. After the seals were placed in the lysimeters, ~0.9 m of soil was added, watered to field capacity, planted with Russian thistle (Salsola kali L.), and placed in a greenhouse. The herbicide trifluralin, which was shown to be effective when encapsulated in a polymeric carrier device (PCD) for slow release (Cline et al. 1982), was placed in the lysimeters at several locations.

After the 90-day growth period, the lysimeters were removed from the rack and split lengthwise by cutting a groove on opposite sides with a circular saw. When one-half of the lysimeter was removed, the following relationships of root elongation to the seals were observed and photographed:

- The asphalt emulsion seal, if properly installed, prevented root passage regardless of treatment.

- Plant roots in the control (no trifluralin) grew to the seal (Figure 42a).
- Trifluralin sprayed on the plug prevented roots from contacting the plug surface directly (Figure 42b).
- Plant roots stopped over 1 in. above the seal surface where the trifluralin was placed in the soil profile 2.5 cm (1 in.) above the seal (Figure 42c).
- The effectiveness of trifluralin as a root barrier was negated when it was mixed directly with the asphalt emulsion (Figure 42d).
- Plant roots elongated past the asphalt barrier (herbicide mixed into the emulsion) poured on in a thin layer (Figure 42e).

In tests at the Grand Junction site, trifluralin was applied on sections of the asphalt test plot. Two application methods were used: 1) spray-on at 5 to 10 times the rate used for 1 year's weed control in an agricultural area and 2) PCD pellets placed at 6.3- and 12.6-cm (2.5- and 5.0-in.) intervals. In both tests, 5 cm of sand was placed over the asphalt before the trifluralin was applied and then 30 to 90 cm (1 to 3 ft) of topsoil was placed over the top. Both systems were effective at halting root growth above the seal without any serious effects on plant growth. After 1 year, the PCD system showed promise as an effective long-term means of limiting root growth.

Special animal barrier test facilities (Figure 43) were constructed at Richland, Washington, and Grand Junction, Colorado, to test the effectiveness of asphalt/aggregate admix, coarse crushed rock, and round rock against the burrowing activities of Townsend ground squirrels and white-tailed prairie dogs. At both sites, neither animal was able to penetrate the asphalt admix seal, although the prairie dogs were able to penetrate several of the rock barriers. It appears that large angular rock would be the most effective rock barrier.

FIGURE 42. Lysimeters Used for Plant Intrusion Studies

FIGURE 43. Animal Barrier Test Facility

ENGINEERING SPECIFICATIONS

Based on laboratory studies and field test results, engineering specifications have been developed for applying asphalt emulsion radon barrier systems on uranium mill tailings piles including materials specifications, construction specifications, and cost estimates. These engineering specifications are intended to serve as a guide for the final design of an asphalt radon barrier system by a remedial action contractor.

MATERIALS SPECIFICATIONS

An asphalt radon barrier seal consists of an asphalt emulsion/aggregate admix. Specifications for the asphalt emulsion and the aggregate are to be used for initial selection of candidate emulsions and aggregates. The fact that the emulsions and aggregates meet these specifications does not insure that an acceptable admix will result. The resulting admix must be tested and must meet separate specifications, which are the ultimate test. Specifications for asphalt emulsion, aggregate, asphalt/aggregate admix, and site-specific formulations for many of the high-priority western sites are discussed below.

Controlled-Set Asphalt Emulsions

An asphalt emulsion consists of three basic ingredients: asphalt, water, and an emulsifying agent that allows the asphalt and water to mix. Asphalt emulsions are divided into three categories: anionic, cationic, and nonionic. Anionic emulsions contain negatively charged particles that would migrate to a positively charged pole or anode. Cationic emulsions have positively charged particles that would migrate to the cathode. Since most aggregates are negatively charged, cationic emulsions are generally used for asphalt/aggregate admixes to provide firm bonding between the asphalt and the aggregate.

Emulsions are further classified on the basis of how quickly the asphalt will coalesce (revert to asphalt cement). The terms RS, MS, and SS (rapid setting, medium setting and slow setting) have been adopted to simplify and standardize this classification. RS emulsions react with surfaces such as those on the aggregate and break quickly. The asphalt sticks to the aggregate and the water separates. True slow-set emulsions mix with the aggregate but interact

only in a limited manner; they break by evaporation of water. In between these two are MS or controlled-set emulsions. This category also includes many SS emulsions.

Controlled-set emulsions mix with aggregate quite freely for a period of time and then setting begins. The mixing and setting times for these emulsions are affected by the type of aggregate, environmental conditions, and chemical additives. Controlled-set emulsions are most appropriate for radon barrier systems. Controlled-set emulsion specifications are shown in Table 27. These specifications should be used for selection of candidate emulsions to be used for admix testing.

Aggregates

Aggregates make up the majority of the admix and have a variety of physical and chemical properties that have a marked influence on the properties of the admix. These properties include particle size distribution, shape, density, and the nature of the fines. Frequently, there are too many fines and the fines are plastic (clay-like).

TABLE 27. Controlled-Set Emulsion Specifications

<u>Tests on Emulsion</u>	<u>ASTM</u>	<u>Specification</u>
Viscosity at 77°F (25°C), SFS	D-88	15 to 40
Storage stability (24 h), %	D-244, sec 56-62	1 (maximum)
Particle charge test	D-244, sec 19-21	Positive (cationic emulsion)
Sieve test, %	D-244, sec 38-41	0.1
Distillation residue, wt%	D-244, sec 8-10	60 (minimum)
<u>Tests on Residue</u>		
Penetration, 77°F, 100 g, 5 s	D5	40 to 90
Ductility, 77°F, 5 m/min, cm	D113	40 (minimum)
Solubility in trichloroethylene, %	D2042	97.5 (minimum)

Originally, uranium tailings were to be used as the aggregate. This approach was abandoned because of the large variation in particle size distribution within the tailings, particularly the large quantities of fines. It was determined that ASTM fine concrete sand should be the specification material. This sand is similar to Type 1 aggregate specified by the International Slurry Seal Association (ISSA 1979). Sieve analysis for the two types of aggregate are shown in Table 28. The average gradation of mortar or concrete sand samples obtained near five high-priority sites and the gradation of the 1981 Grand Junction field test aggregate are also indicated.

Concrete sand particles tend to be a little bit larger than sand used for slurry seals. When slurry seal sand was used for radon barrier systems, the set was a little harder, probably because the fines were smaller than 200 mesh. It would be desirable to have a few more fines in the aggregate than concrete sand typically has. In addition, it appears that a well-graded aggregate is preferable to a narrow-graded aggregate.

Several other specifications for slurry seal aggregate (as recommended by the ISSA) are shown in Table 29. The use of these specifications for aggregates for radon barrier systems has not been evaluated. Ultimately, the selection of aggregate will be based on availability and performance in the admix tests.

TABLE 28. Particle Size Distribution of Aggregates

Sieve Size	ASTM Concrete Fine Aggregate, % Passing	ISSA Type 1 Aggregate, % Passing	Concrete or Mortar Sand, % Passing	Grand Junction Field Test Aggregate, % Passing
9.51 mm (3/8-in.)	100	100	100	100
4.75 mm (No. 4)	95 to 100	100	99	--
2.36 mm (No. 8)	80 to 100	90 to 100	88	75
1.18 mm (No. 16)	50 to 85	65 to 90	73	--
600 μ m (No. 30)	25 to 60	40 to 60	56	55
300 μ m (No. 50)	10 to 30	25 to 42	26	--
150 μ m (No. 100)	2 to 10	15 to 30	6	8
200 μ m (No. 200)	--	10 to 20	2	3

TABLE 29. Recommended Specifications for Slurry Seal Aggregates^(a)

Characteristics	ASTM Test Method	Specifications
Sand equivalent (plastic fines)	D2419	45 (minimum)
Soundness of aggregate using sodium sulfate or magnesium sulfate	C88	15% (minimum)
Abrasion of aggregate using Los Angeles machine	C131	35 (maximum)

(a) ISSA (1979).

Asphalt/Aggregate Admixtures

The ultimate test of the asphalt emulsion and aggregate is the ability to produce an admixture that: 1) can be placed over the mill tailings using standard paving equipment (cold mix paver), 2) forms a seal that is an effective radon barrier, and 3) is strong enough to withstand mechanical forces involved in field application (for example, overburden application).

To be applied with a cold mix paver, the asphalt emulsion and aggregate must mix for a period of time in the paver without setting. The holdup time in the cold mix paver during the 1981 field test was ~1/2 min. In addition, time is sometimes required for handworking the material (filling seams and difficult-to-reach spots) before it sets. Based on this, a mix time of ~2 min is required. After that, the admixture should set fairly rapidly (5 min was chosen for the desired set time) to avoid run-off and separation of the asphalt and the aggregate. A mix design classification test was developed that determines the mixing and setting times of asphalt/aggregate formulations. The procedure for this test is included as Appendix A. The classification test is used to select compatible asphalt emulsions and aggregates before field application and is used in the field to verify the quality of the asphalt and aggregate delivered to the field site.

Laboratory studies have shown that a thin, poured-on asphalt emulsion seal is as effective as an asphalt aggregate admix. The admix is used only to provide strength for field applications. Thus, a continuous asphalt phase is all that is necessary for an effective radon barrier and admix failure is due to

radon transport through cracks or interconnected voids in the admix. Admixtures containing 10% to 12% asphalt (wt% of dry aggregate) as is common in slurry seals do not stop water vapor or radon, and 12 to 14 wt% asphalt seals stop only water vapor. At 18 wt% asphalt, radon fluxes were reduced by more than 99.9%. A 22 wt% asphalt admixture was specified for field application to allow a safety factor for mixing and application inconsistencies. Table 30 shows the specifications for asphalt/aggregate admixtures to be used for radon barrier seals.

Formulation Design Procedure

The objective of this design procedure is to formulate an effective asphalt/aggregate admixture using the least costly locally available materials. The following procedure should be followed:

1. Evaluate locally available asphalt emulsions and aggregates
 - a) Calculate quantity required
 1. Determine area to be covered in m^2
 2. Asphalt: 34 ℓ emulsion/ m^2 (63 wt% asphalt) or 21 ℓ asphalt/ m^2
 3. Aggregate: 0.1 MT/ m^2
 - b) Obtain asphalt emulsion samples
 1. Appendix B lists asphalt emulsion producers near uranium mill tailings sites.
 2. Specifications as determined by supplier must meet specifications listed in Table 30.
 3. Must be available in quantity required (see 1.a.2).
 - c) Obtain samples of local aggregates
 1. Particle size distribution should be similar to those listed in Table 28.
 2. Must be available in the quantity required (see 1.a.3).
2. Formulation design

- a) Determine whether various formulations of asphalt emulsion and aggregate meet the specifications in Table 30.
- b) If more than one formulation meets the specifications, make final selection based on availability and cost.
- c) After the final selection is made, the admixture radon diffusion characteristics should be determined by PNL.

TABLE 30. Asphalt/Aggregate Admixture Specifications

<u>Characteristic</u>	<u>Specification</u>
Mix design classification test, 25°C	
Mix time, min	2 (minimum)
Set time, min	5 (minimum)
Other	No false slurry
Asphalt content, ASTM D2072	22 (average)
(g asphalt/g dry aggregate) x 100	18 (minimum)
	26 (maximum)
Helium leak test	Passing

Site-Specific Formulations

Five sites were selected to develop site-specific formulations: Rifle, Grand Junction, and Durango, Colorado; Riverton, Wyoming; and Salt Lake City, Utah. Locally available aggregates, usually concrete or mortar sand, were obtained from the five sites. Table 31 shows the gradations of the aggregates used in this study.

Emulsions or base asphalts were obtained from four sources. Bituminous Materials Co., Inc., Albuquerque, New Mexico, supplied three emulsions; Armak supplied one emulsion similar to that used for the 1981 Grand Junction field test; and Petroleum Sciences, Inc., made several emulsions using base asphalt from Utah Emulsions in Salt Lake City and CONOCO in Denver. CONOCO supplies asphalt to Colorado Bitumuls, which sells emulsions in Denver and Grand Junction. Emulsifiers used by Petroleum Sciences were obtained from Armak, National Research and Chemicals, Westvaco, Tomak, and Sherex. A complete list of the emulsions tested is shown in Table 32.

TABLE 31. Aggregate Gradations for Site-Specific Formulations

Sieve Size	Washed Gradation, % Passing				
	Riverton, Wyoming	Rifle, Colorado	Grand Junction, Colorado	Durango, Colorado	Salt Lake City, Utah
3/8 in.	100	-	100		
#4	97.7	100	99.9	100	100
#8	83.9	86.4	82.6	89.1	99.5
#16	71.2	69.4	67.4	66.2	92.4
#30	55.4	48.8	56.5	42.3	76.1
#50	24.6	21.6	28.6	19.7	38.4
#100	6.6	6.5	6.7	5.0	6.7
#200	2.8	2.5	2.5	2.0	1.7

Each emulsion listed in Table 32 was mixed with at least one aggregate and the mixing qualities were assessed. The most promising mixtures were selected for further testing. At least one emulsion was found that would set with each aggregate. The properties of these emulsions and the resulting admixes are shown in Table 33.

It was particularly difficult to find an emulsion that would set with the Durango and Riverton aggregates. In addition, a considerable number of the "sets" were soft (would not stall the mixer in the mix design classification test) yet appeared to produce a good admix.

All of the aggregates selected for this study were concrete sands and thus were low on percent passing the #200 sieve. One of the causes of slow and soft setting appears to be a lack of fines, although the high level of asphalt emulsion used might also have contributed to the setting differences. This problem does not appear to be serious since the mixes that went into false slurry appeared to work well when placed and compacted. Since the tailing piles do not have traffic, the problems of the soft or false slurry do not occur as they do with slurry seals.

TABLE 32. Asphalt Emulsions Used for Site-Specific Formulations

Source of Asphalt or Emulsion	Emulsifier	wt% Asphalt	Viscosity, 77°F SFS
Utah Emul.	Armak E-11, 1%	61.0	-
Utah Emul.	Tyfo A, 1%	(60)	-
Utah Emul.	Armak E-52, 1%	-	-
Utah Emul.	Sherex AA 57, 1%	60.1	-
Utah Emul.	Tyfo A, 1.0%	61.2	-
Utah Emul.	Tyfo A, 0.75%, Tyfo B, 0.25%	60.2	24
Utah Emul.	Tyfo A, 0.50%, Tyfo B, 0.50%	63.5	23
CONOCO	Armak E-11, 1%	54.3	15.5
CONOCO	Armak E-52, 1%	59.6	18.0
CONOCO	Sherex AA 22, 1%	62.7	26.0
CONOCO	Sherex AA 57, 1%	55.0	16.0
CONOCO	Tyfo A, 1%	64.0	-
CONOCO	Tyfo A, 1%	63.6	-
CONOCO	Indulin MQK	63.7	-
CONOCO	Tyfo A, 1%	59.5	24
Armak	Unknown	66.0	40
CQS Emul. from Bituminous Materials ^(a)		62.5	-
CQS Emul. from Bituminous Materials ^(a)		-	-
CQS Emul. from Bituminous Materials ^(a)		-	-
CONOCO	TAE-T, 1%	62.2	19.0
CONOCO	TAE-Q, 1%	64.1	20.0
CONOCO	TAE-D, 1%	61.9	16.5
CONOCO	Tyfo A, 1%	61.5	17.0
CONOCO	Tyfo A, 0.75%; Tyfo B, 0.25%	63.1	14.3
CONOCO	Tyfo A, 0.50%; Tyfo B, 0.50%	--	--

(a) This emulsion comes ready-mixed; the emulsifier is unknown.

Some of the emulsions shown in Table 33 did not meet all specification requirements, although they did work. Two did not pass the storage stability test, which was not unexpected because they were both laboratory produced and had been stored for a considerable time. If used commercially, the storage stability would surely be brought within specification through normal adjustments that a commercial plant would make.

TABLE 33. Test Data on Site-Specific Formulations

	35-38A 1% Tyfo A with CONOCO Asphalt	35-69D 1% Tyfo A with Utah Asphalt	Bituminous Materials #7159	Specification
Viscosity at 77°F, SFS	17	24	22	15 to 40
Storage stability (24 h), %	8	0.5	13	1 (maximum)
Mix design classification test at 25°C				
Mix time, min	(a)	(a)	(a)	2 (minimum)
Set time, min	(a)	(a)	(a)	5 (minimum)
Other	(a)	(a)	(a)	No false slurry
Particle charge	Positive	Positive	Positive	Positive
Sieve test, %	0.44	Passed	Passed	0.10
Distillation test, residue, %	64.3	57.4	62.5	60 (minimum)
<u>Tests on Residue</u>				
Penetration, 25°C 100 g, 5 s	64.5	88	107	40 to 90
<u>Ductility at 77°F</u>				
5 cm/min, cm	150+	150+	108	40 (minimum)
Solubility in trichlorethylene, %	99.70	99.98	99.95	97.5 (minimum)
Asphalt content, wt%	64.3	57.4	62.5	60 to 70
Aggregate employed	Rifle Grand Junction Durango	Riverton Vitro	Durango	

Mixing tests were made and set times were adjusted with $\text{Al}_2(\text{SO}_4)_3$ solution as necessary to arrive at a set time of more than 5 min. The mix time as defined in the mix design classification test does not appear to be significant and often is nearly undetectable. The set time specification should be a range such as 3 to 6 min and false slurry should be allowed since it does not appear to seriously affect the admix performance.

These studies show that asphalt admix seals can be formulated from locally available materials. The information given can serve as a guideline for developing formulations for other western sites.

CONSTRUCTION SPECIFICATIONS

This section describes a procedure for applying an asphalt admix seal based on three field tests at the Grand Junction tailings pile. It may be necessary to modify the procedure at other sites.

Site Preparation

Site preparation is particularly important for smooth operation of equipment and for seal integrity. The surface must provide good support for the equipment and must be smooth enough to prevent penetration of the seal by surface anomalies. Field tests have shown that in most cases it is not possible to pave directly over the tailings because they do not provide enough support for the equipment. Field applications have been successfully completed on both compacted overburden and compacted road base gravel. At least 6 cm of overburden or gravel should be placed over the tailings and compacted. If the overburden is clay, it may not be possible to pave in wet weather. If road base gravel is used and the site is sloped, the wheels of the paver may eventually pick up asphalt, which will in turn pick up some of the road base. These clumps of asphalt and road base can cause seal discontinuities that will have to be repaired.

If possible the site should be contoured so that the slope is generally all in one direction; the highest or lowest part of the site should not be in the middle. Such a slope allows the paver to pave in one direction and reduces

the amount of handwork that is required to make the seams. The slope should not exceed ~12%. For a flat site or slopes of 3% or less, the paver can pave uphill or across the slope. When going across the slope, paving should begin at the bottom and work toward the top.

An area must be developed to stockpile at least a 1-week supply of aggregate. At an asphalt rate of 95,000 ℓ /day (25,000 gal/day), this corresponds to about (840 m^3) of aggregate. An area ~18 m x 18 m (60 x 60 ft) is required to store this much aggregate. This area should be covered with (5 to 10 cm) of compacted road base to prevent contamination of the aggregate with earthen materials or tailings.

The site should be developed so that a boundary area completely surrounds the tailings. This area should contain a gravel road and provide room for the paver to maneuver into position at the beginning and end of each pass. The width of the boundary layer should be 25 to 30 m.

Application Equipment

Application of an asphalt seal will involve the use of the following equipment:

- cold mix paver (Midland Model 701 or equivalent)
- three rear dump trucks (7.7- m^3 capacity)
- one front end loader (2- m^3 capacity)
- two asphalt distribution trucks.

Cold Mix Paver

The Midland Model 701 (shown in Figures 15 and 23) is a self-propelled mobile plant designed and built to mix and place cold asphalt mixtures in a continuous operation. The pug mill can produce 180 tons of mixed material per hour on an average daily basis. The full floating vibratory screed can be set to widths from 2.4 to 3.7 m (8 to 12 ft) and can pave to depths of 23 cm.

The cold mix paver aggregate feed system combines a butterfly folding hopper and constant-speed belt feeder with an aggregate strike-off door for well-controlled delivery of aggregate to the mixer, making proportioning of the mix simple and easy. The mix paver bitumen system contains a variable hydraulic drive with constant displacement bitumen pump (Midland 1977).

Because of the high asphalt (bitumen) content of the seal material, several modifications to the cold mix paver must be made to apply this material. Typical operating conditions at the 1981 field test were 100 lb/min (45 kg/min) of aggregate and 200 gpm (757 ℓ /min) of asphalt emulsion. To reach these conditions, an additional pump and flow indicator were added to the machine. With this modification, the maximum emulsion flow rate was $\sim$ 200 gpm (757 ℓ /min). An aggregate flow rate of 5100 lb/min (2320 kg/min) would require a calibration gate opening height of $\sim$ 2 in. (5 cm). An opening of more than 4 in. (10 cm) is more desirable for good control of the feed rate. The belt conveyor drive motor must be replaced with one that will reduce the belt speed by 50% or more.

Because the admix has a high asphalt content, it flows more easily than the cold mix paver was designed for. Instead of flowing out the back of the screed, a significant portion of the material sloughs out the side and front of the screed, depending on the slope of the paving base. To prevent this, a flexible rubber or plastic skirting should be attached to the front and sides of the distributor screed. This skirting must be flexible enough to maintain a reasonable seal on irregular ground surfaces. A clearance of $\sim$ 1/2 in. is acceptable. A similar modification was made to the Midland paver by Shell Oil Canada to apply a sulfur asphalt (Sand-Asphalt Sulfur 1980).

Filling the paver with asphalt and aggregate takes almost as long as the paving process; to make the best use of time and equipment, the paver must be supplied with aggregate and asphalt during the run, using standard dump trucks and asphalt distribution trucks.

Other Equipment

The paver is designed so that standard 10-yd³ (7.7-m³) dump trucks can back up and hitch onto the paver to load the aggregate hopper without stopping the paver. Three trucks and one front-end loader are required to keep pace with the paver.

The asphalt emulsion is generally delivered in 6,000-gal (23,000-l) insulated trailers that do not have pumps. A distributor truck pumps the emulsion off the trailer, hauls it to the paver, and pumps it into the storage tank.

If the paver stops for more than 5 min, it becomes difficult to make a good seam between the new and old asphalt without considerable handwork. Therefore, close coordination between the paver, the aggregate trucks, and the asphalt trucks is required.

Seal Application

A crew of ~10 people is required for the paving operation: 3 operators for the cold mix paver, 3 aggregate truck drivers, 1 front-end loader operator, 2 drivers for the asphalt distributor trucks, and a foreman.

Before paving, the asphalt pumps and the aggregate feed system must be calibrated. Details on this procedure are discussed in Appendix C. Following calibration, a test strip should be paved and tested for asphalt content. If the asphalt content is 20 to 24 wt% on a dry aggregate basis and the admix has the correct appearance (see Appendix C), paving can begin.

It is desirable to have a flat paving surface so that the paving can be done in any direction. If not, the paving should be done across the slope (for other possibilities, see Appendix C). One aggregate truck will be dumping into the paver hopper at all times during paving. Another will be loaded and ready to replace the truck dumping into the paver. The front end loader will be loading the third truck. One distributor truck will be filling the cold mix paver while the second truck is unloading the asphalt tanker in preparation for filling the paver.

Various problems that may occur during paving and the corrective actions required are discussed in Appendix C.

Field Testing and Quality Assurance

Testing and quality assurance are a very important aspect to construction of a high-quality asphalt radon barrier. Field tests to be used are shown in

Table 34. Visual inspection and monitoring of the application process as discussed in Appendix C are equally as important in ensuring a high quality seal.

Field Tests 1, 2, and 5 will verify the quality and quantity of the asphalt emulsion as delivered. These tests need to be run on each tanker load of emulsion (~4 times per day). Tests 3, 4, and 6 also need to be conducted before startup.

A sample of the admix as applied should be taken once per hour to determine the asphalt content (Test 6). Asphalt content should be between 0.18 to 0.26 kg/kg dry aggregate. Each day two samples from the areas paved on the preceding days should be analyzed to determine the water content. The proper moisture for compaction will be reached in 2 to 4 days in good weather; therefore, about 8 samples will be required each day.

TABLE 34. Field Tests for Asphalt Emulsion, Aggregate, and Admix

Test	Description	Testing Frequency	Typical Results	Limits
1	Water content of asphalt emulsion (ASTM D244)	1/tanker (4/day)	35% to 40%	--
2	Weight of asphalt emulsion per gallon (ASTM D244)	1/tanker (4/day)	8.3 to 8.5 lb/gal 1.0 to 1.02 kg/l	--
3	Moisture content of aggregate	2/day	1% to 5%	--
4	Sieve analysis of aggregate (ASTM C136)	1/day		
5	Mixing and setting times of admix (special procedure)	1/tanker (4/day)	2 min and 5 min	
6	Asphalt content of admix (ASTM D2072)	1/h (8/day)	0.22 kg/kg dry aggregate	0.18 to 0.26
7	Water content of admix (ASTM D95)	2 samples from each preceding day's application every-day until compacted	1% to 10%	Should be compacted at 3% (?)

Post-Treatment

Post-treatment consists of compacting the seal and covering it with overburden. The seal must be compacted to close the small pinholes caused by dehydration and to provide better adhesion between aggregate and asphalt. The overburden protects the admix seal from sun exposure, rain, extreme temperature, and sudden temperature changes. It also reduces oxygen exposure and protects the asphalt from autooxidation initiators in the atmosphere.

Compaction

The admix seal must be allowed to cure before it is compacted. A drying curve for the 1981 Grand Junction field test is shown in Figure 44. To determine the optimal curing time before compaction, a series of six admix samples were compacted with a Marshall hammer at different curing times ranging from 3 to 30 days. Little difference was noted in the density of the sample or the radon diffusion coefficient. This behavior is not surprising because the admix expels most of the water within the first 3 days. Compaction can probably begin as soon as the free water has run out of the seal (~3% moisture), which should to 1 to 3 days after mixing.

The admix should be compacted with a steel-drum vibratory roller such as the one shown in Figure 24. The admix should not be compacted in midday heat in the summer. If the surface is at all tacky, the admix will stick to the roller.

Overburden Application

Approximately 0.6 m (2 ft) of overburden should be placed over the admix seal. The overburden should be dumped and spread in 15- to 20-cm lifts with a dozer or scraper, using care not to damage the admix seal. Seal damage can be minimized by operating heavy equipment, where possible, on areas already covered by overburden. The overburden should be dumped on the asphalt seal and spread by pushing the overburden with a tractor or dozer ahead of the equipment, to prevent the equipment from coming in contact with the asphalt seal. There may be times during the summer when it will be too hot to apply overburden. If the admix is very tacky, overburden should be applied very carefully or not at all. Compaction other than that resulting from the equipment used to transport and spread the overburden is not necessary.

FIGURE 44. Drying Rate for Asphalt Admix (1981 Field Test)

COST OF ASPHALT EMULSION RADON BARRIER SYSTEMS

During the 1981 field test, the actual costs for the asphalt/admix seal were compiled. Based on these results, cost estimates were made for the Durango, Shiprock, and Salt Lake City sites. In addition, the sensitivity of the overall cost of radon barrier systems to various factors was analyzed. The results of these cost studies are detailed by Baker and Hartley (1982) and Baker et al. (1982), and are summarized below.

1981 Grand Junction Field Test Costs

During the 1981 field test, an $\sim 4000\text{-m}^2$ area was covered with 5 to 8 cm of asphalt/aggregate admix and topped with 0.6 m of overburden. In addition, $\sim 900\text{ m}^2$ on an $\sim 16\%$ slope was covered with asphalt/aggregate admix and later compacted and covered with overburden. The cover system is described in detail by Hartley et al. (1981b, 1983).

The actual cost for construction of the asphalt cover was $\$27.20/\text{m}^2$ (Table 35). All subcontractor costs and PNL costs incurred at the test site are included; PNL costs associated with engineering and planning the field test are not included. Materials, primarily the asphalt emulsion, were the major cost item.

More efficient utilization of labor, equipment, and materials, which would be possible in a full-scale operation, would reduce the cost of the asphalt cover. Approximately 57,000 ℓ /day (15,000 gal) of emulsion was applied with a high of 79,000 ℓ /day (21,000 gal) during the field test. An application rate of 95,000 ℓ /day (25,000 gal) should be easily achieved in a full-scale operation. In addition, $\sim 20\%$ of the labor and equipment charges were for calibration and shakedown of the equipment prior to the actual paving. A significant quantity of materials, mainly the concrete sand, was not used, resulting in extra costs. Overall, about $\$2$ to $\$3/\text{m}^2$ could be saved in a full-scale operation.

Site-Specific Cost Estimates

Based on the 1981 field test data and discussions with contractors and asphalt emulsion suppliers, the costs of asphalt/aggregate cover systems for Durango, Shiprock, and Salt Lake City were estimated. Two or three disposal locations were selected for each site based on Ford, Bacon, and Davis Utah Inc. assessments of potential disposal locations (FBDO 1981a,b,c). The cost for each disposal location is shown in Table 36. The costs do not vary much from site to site but are lowest in the Salt Lake City area due to the proximity of asphalt emulsion suppliers.

TABLE 35. 1981 Grand Junction Field Test Costs

Item	No. of Units	Cost/Unit, \$	Total Cost, \$
Material cost			
3/4 in. road base gravel, yd ³	573	7.40	3,700
Concrete sand, yd ³	631	11.45	7,220
Asphalt, gal	45,000	1.35	60,750
Adobe clay (overburden), yd ³	4750	3.00	14,250
Total materials cost			85,920
Equipment cost^(a)			
Cold mix paver and 2 operators	Midland 701 at \$10,500 + \$1500/day		16,815
Vibratory tandem roller	Bomag BW 220A at \$3500/month		3,753
Front-end loader and operator	2 m ³ and \$45/h		1,755
Grader and operator	\$50/h		486
Dump trucks and operator	7.7 m ³ and \$30/h		2,070
Water truck and operator	7600 l and \$35/h		2,761
Asphalt tankers	24,000 l		(b)
Total equipment cost			27,640
Labor cost ^(c)			19,600
Total materials, equipment, and labor cost			133,160
Cost, \$/m ²			27.20 ^(d)

(a) Includes subcontractor labor.

(b) Included in the cost of the asphalt.

(c) Primarily PNL labor.

(d) This amount would be about \$28/m² if the entire test area was covered with overburden.

TABLE 36. Estimated Cost of Asphalt/Aggregate Cover System for Three High-Priority Western Sites

	Cost, \$1000 (1981)						
	Durango, Colorado		Shiprock, New Mexico		Salt Lake City, Utah		
	East Ridges	Bodo	Many			Sager's	In
	Basin	Canyon	Devils	Rattlesnake	Clive	Flat	Place
Tailings stabilization	180	210	410	260	340	360	540
Application of asphalt seal	1910	2180	4360	2720	3025	3820	3970
Overburden	<u>350</u>	<u>470</u>	<u>840</u>	<u>640</u>	<u>570</u>	<u>610</u>	<u>2300</u>
Total	2440	2860	5610	3620	3940	4790	6810
Engineering and Construction							
Management (30% of \$2440)	<u>450</u>	<u>520</u>	<u>990</u>	<u>610</u>	<u>800</u>	<u>880</u>	<u>1590</u>
Total	2890	3380	6600	4230	4740	5670	8400
Contingency (30% of \$2890)	<u>870</u>	<u>1010</u>	<u>1980</u>	<u>1270</u>	<u>1420</u>	<u>1700</u>	<u>2520</u>
Total	3750	4390	8580	5500	6160	7370	10920
Cost, \$/m ²	26.50	27.10	26.50	27.20	23.40	26.00	24.50

Sensitivity Analysis

Several factors could significantly affect the cost of asphalt/aggregate radon barrier systems. Because the asphalt emulsion accounts for nearly half of the total cost, the most significant factors are the amount of asphalt required and the cost of the asphalt emulsion. Laboratory studies have shown that the minimum asphalt content in the admix that will retain radon is ~22 wt% on a dry aggregate basis. Therefore, the only way to reduce the amount of asphalt used is to reduce the thickness of the seal. The effect of seal thickness on total cost is shown in Figure 45.

The cost of asphalt emulsion also has a significant impact on the cost of the cover. Discussions with Armak, McCook, Illinois and Petroleum Sciences, Inc., Spokane, Washington, indicated the price of asphalt emulsion such as the one used for the field test--cationic medium-set (CMS-2) containing 63 wt% asphalt--is \$155 to \$200/MT (\$0.15 to \$0.20/l) at the emulsion mix plant. Because most of the sites are located some distance from an emulsion plant, the transportation charges are significant. For the site-specific cost estimates, the delivered costs ranged from \$0.21 to \$0.33/l (\$0.80 to \$1.25/gal) depending

FIGURE 45. Effect of Seal Thickness and Asphalt Cost on the Cost of Asphalt Admix Seals

on the location of the site. Discussions with suppliers of asphalt and asphalt emulsion indicated that the price of asphalt will probably remain stable or possibly drop in the short term. In the long term, prices will probably increase somewhat faster than inflation.

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APPENDIX A

MIX DESIGN CLASSIFICATION TEST

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MIX DESIGN CLASSIFICATION TEST

1. Summary of Method

This procedure consists of mixing the asphalt emulsion with the aggregate in a specially designed apparatus powered by a synchronous motor that provides a feedback of the torque required to mix. The torque is recorded over time to provide a profile of the mixing and setting phenomena. The mixer is started empty, the aggregate is placed in the container, and then the emulsion is added. From the shape of the graph obtained during mixing, it is possible to determine mixing characteristics.

2. Significance and Use

This procedure is an objective method to evaluate the setting properties of mixtures of aggregate and asphalt emulsion. It was specially developed to measure the setting properties of mixtures in which the asphalt emulsion is of a type that provides a controlled set (a mixture that is quite fluid at first but gradually thickens and then solidifies). This tool may be used to direct the development of controlled-set emulsions and to design mixes placed in the field.

3. Apparatus

3.1 Container. The container resembles a 1-quart paint can from which the top rim has been removed. If tests are to be run at various temperatures other than ambient, a special water-cooled container may be built so that mixing temperature may be controlled or the container may be placed in a controlled water bath.

3.2 Mixer. The mixer consists of a synchronous motor/generator driven by a control box that allows a speed control of 0 to 300 rpm. The motor/generator allows feedback of the torque required to operate at the desired speed and provides for the ability to set a predetermined stall torque. The output is recorded on chart paper to provide the profile of the set.

3.3 Mixing Blade. A special mixing blade consists of mixing bars and a wire sweep to keep the bottom mixed. The blade or its design will be supplied by PNL.

3.4 Recorder. A recorder capable of reading 0 to 200 mV full scale is attached to the control box.

4. Conditioning and Sample Preparation

The temperature and aggregate gradation have a marked effect on the results of the test.

4.1 Temperature

4.1.1 Tests Run at Ambient Temperature

4.1.1.1 Place the emulsion container in a controlled water bath at the desired temperature (within $\pm 0.1^{\circ}\text{F}$).

4.1.1.2 Place a container of water in the water bath and any other solution of additives that might be used.

4.1.2 Tests Run at Other than Ambient Temperature

4.1.2.1 Place liquid additives in controlled water bath at the desired temperature (see 4.1.1.1 and 4.1.1.2).

4.1.2.2 Put the mixer into the water bath to condition.

4.1.2.3 If the temperature is close to ambient temperature and it is possible to change the room temperature, adjust the ambient temperature to approximately that of the test. Put can in water bath to condition. If the temperature is not room temperature, provide a waterbath to surround the mixing container during the test.

4.1.2.4 Put the aggregate samples in water-tight plastic bags and place in the water bath to condition.

4.1.2.5 Condition all components for at least 1 hour at the desired temperature.

4.2 Aggregate

The gradation of the aggregate can have a profound effect on the set time, greatly reducing precision. The aggregate must therefore be separated and recombined accurately.

4.2.1 Dry sieve all aggregate to be used in a particular study over the following sieve sizes: 3/8, 4, 8, 16, 30, 50, 100, 200. Weigh the amount retained on each sieve and place in separate containers.

4.2.2 Determine the dry gradation, calculated as a % between each sieve size, i.e., $-3/8 + 4 = x\%$, $-4 + 8 = y\%$, etc.

4.2.3 Multiply 3 x % retained in each fraction (should give 300 grams per sample).

4.2.4 Make up the number of samples needed for the study, place in water-tight plastic bags and condition to the test temperature.

5. Procedure

5.1 Start the servocontrol and adjust the speed to 50 rpm. Adjust the torque control so that the motor will stall at 180 mV. Turn motor off.

5.2 Set the recorder to full scale 0 to 200 mV and the chart to 2 cm/min.

5.3 Place mixing can in apparatus and adjust mixing blade so that it is just above the bottom.

5.4 Start the mixer; the recorder should register a straight line at ~20 mV.

5.5 Hand mix the water and other additives into the aggregate, pour set mix into mixer, and mix for ~30 s. The pen on the recorder should fluctuate widely between 60 and 80 mV.

5.6 Add the emulsion. The recorder pen will show a sharp momentary increase, then a drop, and then fluctuate in a band of ~6 mV between the 30- and 40-mV range.

6. Data Interpretation

A typical recording of an asphalt/aggregate mixture during setting is shown in Figure 6a.

6.1 Setting Abnormalities

- 6.1.1 No set. If the emulsion is of a type that will not set, such as a slow set emulsion, the graph will be a horizontal band about 6 mV wide for as long as mixing occurs.
- 6.1.2 False Slurry. False slurry is a condition where the emulsion/aggregate system does not set but transforms into a thick, pasty mixture. Figure 6b shows a typical graph.
- 6.1.3 Premature Set. Figure 6c shows a graph typical of the case where setting starts immediately, before full mixing has occurred.
- 6.1.4 Aggregate Stripping. In some cases, the mixture sets but is soft enough so that the mixer can still mix. In this case, the shear of the mixer breaks up the system and strips the asphalt from the aggregate. Figure 6d shows a typical recording.

6.2 Mixing Parameters

Mixing properties may be divided into two sections: a mixing time and a setting time. Both may be described by several parameters.

- 6.2.1 Mix Time. The mixing time is defined as the time from the introduction of emulsion to when the trace on the graph ceases to be horizontal. At the end of the mixing time, the band traced on the chart paper will make a small discontinuous jump of 1 to 2 mV after which the band will increase linearly.
- 6.2.2. Set Time. The set time is defined as the time required for the torque/time profile to approach the vertical.
- 6.2.3 Calculation of Setting Parameters. For systems in which there exists a mixing time (no premature set), the setting process may be described by the following formula:

$$\Delta S = mt + Ae^{Bt}$$

where ΔS = the increase in torque above which the second state (discontinuous jump and linear increase) begins

m, A, B = constants

t = time.

7. Report

- 7.1 If the slurry sets too fast or does not set, report those facts only.
- 7.2 If the curve shows that the slurry went into a false slurry condition, report that fact, the mixing time, and the constant m of the linear portion of the curve.
- 7.3 For the curves of good slurry, report the mixing time, the setting time, and the constants m , A , and B in the equation, if requested.

Report

- 1.1. If the slurry sets too fast or does not set, report those facts only.
- 1.2. If the curves show that the slurry went into a false slurry condition, report that fact, the mixing time, and the constant k of the 10 sec portion of the curve.
- 1.3. For the curves of good slurry, report the mixing time, the setting time, and the constant k . Use k in the equation, $t = \frac{10}{k}$.

APPENDIX B

ASPHALT EMULSION SUPPLIERS

APPENDIX B

ASPHALT EMULSION SUPPLIERS

Oregon

Lakeview Tailings Site

Basic Resources, Inc.
End of Pitt Road
Redding, CA 96001
(916) 241-1364

Witco Chemical Corporation
Golden Bear Division
P.O. Box 231
Klamath Falls, OR 97601

Idaho

Lowman Tailings Site

Husky Oil Company
P.O. Box 5713
Boise, ID 83705
(208) 342-7754

Idaho Asphalt Supply, Inc.
800 North Sugar Avenue
Nampa, ID 83657
(208) 466-9541

Other Possible Sources

Utah Emulsions Company
95 West, 1100 North
P.O. Box 248
North Salt Lake, UT 84054
(801) 295-4454

Utah

Vitro and Green River Tailings Sites

Phillips Petroleum Company
383 S. 800 West
Woods Cross, Utah 84087
(801) 295-2311

Utah Emulsions
(see address under Idaho)

Arizona Refining
Highway 89A North
Fredonia, Arizona 86022
(602) 643-2614

Mexican Hat Tailings Sites

Same as Vitro Tailings Pile; also

Chevron USA, Inc., Asphalt Division
3050 S. 19th Avenue
Phoenix, Arizona 85009
(602) 258-7996

Chevron
600 W. Simpson
Tucson, Arizona 85726
(602) 623-0511

Sahuaro Petroleum & Asphalt Company
731 N. 19th Avenue
P.O. Box 6536
Phoenix, Arizona 85005

Ted R. Jenkins Co., Inc.
2532 S. 15th Avenue
Phoenix, Arizona 85002
(602) 254-0496

Western Emulsions, Inc.
1015 S. Freeway
Tucson, Arizona 85705

Arizona

Monument Valley Tailings Site

Same as Mexican Hat, Utah

Tuba City Tailings Site

Chevron USA, Inc., Asphalt Division
Phoenix and Tucson, Arizona
(see address under Mexican Hat, Utah)

Sahuaro Petroleum & Asphalt Company
(see address under Mexican Hat, Utah)

Ted R. Jenkins, Co., Inc.
(see address under Mexican Hat, Utah)

Western Emulsions, Inc.
(see address under Mexican Hat, Utah)

Colorado

Maybell, Rifle, Grand Junction, Gunnison and Naturita Tailings Sites

Utah Emulsions
(see address under Idaho)

Phillips Petroleum Company
(see address under Vitro, Utah)

Colorado Bitumuls Company, Inc.
P.O. Box 175
5301 N. Bannock Street
Denver, Colorado 80201
(303) 623-0942

Colorado Bitumuls Company, Inc.
P.O. Box 59
Grand Junction, Colorado 81502
(303) 243-6857

CONOCO, Inc.
P.O. Box 16104
Denver, Colorado 80216
(303) 288-6861

Durango Tailings Site

Colorado Bitumuls Co., Inc., Denver and Grand Junction, Colorado
(see address under Maybell et al., Colorado)

CONOCO, Inc.
(see address under Maybell et al., Colorado)

Chevron USA, Inc., Asphalt Division
2040 Second Street, S.W.
Albuquerque, New Mexico 87102
(505) 243-5579

Southwest Emulsions, Inc.
4949 Edith Blvd. N.E.
Albuquerque, New Mexico 87107
(505) 344-3526

Other Possible Sources

Navajo Refining Company
P.O. Box 159
Artesia, New Mexico 88210
(505) 746-9851

New Mexico

Shiprock Tailings Sites

Arizona Refining
(see address under Vitro, Utah)

Colorado Bitumuls Co., Inc., Denver and Grand Junction, Colorado
(see address under Maybell et al., Colorado)

Southwest Emulsions, Inc.
(see address under Durango, Colorado)

Wyoming

Riverton, Converse, and Baggs Tailings Sites

Utah Emulsions Company
95 West, 1100 North
P.O. Box 248
North Salt Lake, UT 84054
(801) 295-4454

Husky Oil Company
P.O. Box 380
Cody, WY 82414
(307) 578-1000

Other Possible Sources

CENEX
P.O. Box 909
Laurel, MT 59044
(406) 252-9326

Chevron USA, Inc., Asphalt Division
(see address under Durango, Colorado)

Ambrosia Lake Tailings Site

Western Emulsions, Inc.
(see address under Mexican Hat, Utah)

Southwest Emulsions, Inc.
(see address under Durango, Colorado)

Chevron USA, Inc., Asphalt Division
(see address under Durango, Colorado)

Navajo Refining Company
(see address under Durango, Colorado)

North Dakota

Belfield and Bowman Tailings Sites

Asphalt Products Company
1 Main Street
Pillsbury, ND 85065
(701) 637-2261

Koch Asphalt Company
P.O. Box 2397
Pillsbury, ND 58065
(701) 945-2761

Hills Materials Company
P.O. Box 2320
Rapid City, SD 57709
(605) 342-3875

Texas

Falls City Tailings Site

American Petrofina
P.O. Box 1011, Mount Pleasure
Garland, TX 75455
(214) 572-3416

Cosdon Oil and Chemical Company
P.O. Box 1311
Big Springs, TX 79720
(915) 263-7661

Gulf States Asphalt Company, Inc.
P.O. Box 508
South Houston, TX 77587
(713) 941-4410

Rifle Petroleum Company
P.O. Box 771
Pleasanton, TX 78064
(512) 569-5210

Slurry Seal, Inc.
P.O. Box 7677
Waco, TX
(730) 195 SS WAC

Texas Emulsions, Inc.
P.O. Box 9520
Allandale Station
Austin, TX 78766
(512) 345-0977

Pennsylvania

Canonsburg Tailings Site

Chevron USA, Inc.
Asphalt Division
13 Mellon Street
Pittsburgh, PA 15144
(412) 361-3900

Russell Standard Corporation
Mercer Branch, Box 509
Mercer, PA 16137
(412) 748-3700

Valley Emulsion Company
P.O. Box 148, Rt. 837
Walton Road
Florence, PA 15039
(412) 462-5111

Western Emulsions
Butler, PA 16001
(412) 586-7761

Wyandotte Blacktop, Inc.
P.O. Box 567
Marion, OH 43302
(614) 383-6343

APPENDIX C

PROCEDURE FOR APPLYING AN ASPHALT/AGGREGATE RADON SEAL
WITH A COLD MIX PAVER

APPENDIX C

PROCEDURE FOR APPLYING AN ASPHALT/AGGREGATE RADON SEAL WITH A COLD MIX PAVER

CREW

A 10-person field crew is necessary for operation of the paving machine. Major hand work (if necessary) will require one more person.

Cold Mix Paver

- operator/driver - controls the speed and direction of the machine, the emulsion flow rate, the screed height, and the distribution auger.
- feed hopper operator - coordinates the dump truck exchanges, observes aggregate feed belt operation, and adjusts calibration gate opening.
- screed operator - stands on the screed and measures the depth and observes the quality of the seal; assists the driver in maintaining the quality of the seal; and performs small hand repairs as necessary.

Aggregate Trucks

- truck drivers
- front-end loader operator

Asphalt Distributor Truck

- truck drivers

Supervision

- foreman - coordinates paving effort and observes seal quality; assists distributor truck operators in making connection to the paver.

APPLICATION PROCEDURE

This section covers the preliminary steps required before paving and the actual paving procedure. Testing and quality assurance requirements are also discussed.

Equipment Shakedown

The following items need to be checked before operation of the cold mix paver:

- Step 1 - Make sure all pumps and motors are operable, especially the additional asphalt emulsion pump and the new belt drive motor.
- Step 2 - Check asphalt storage tank to make sure it is empty and clean.
- Step 3 - Review operational procedure with cold mix paver operators and rest of crew.
- Step 4 - Check dump trucks to make sure they can mate with the aggregate feed hopper on the paver. Drivers should practice backing up to paver.
- Step 5 - Check connections and pumping options between distributor truck and paver.

Paver Calibration and Testing

These steps should be taken before initial startup and approximately once per week thereafter until the paving is completed:

- Step 1 - Obtain tare weight of dump truck and then fill to normal height with the aggregate to be used.
- Step 2 - Sample and determine moisture content of aggregate.
- Step 3 - Set calibration gate height to 5 in. (~13 cm).
- Step 4 - Dump aggregate into cold mix paver hopper and determine with a stop watch how long it takes to feed the aggregate.
- Step 5 - Repeat Steps 1, 3, and 4 for at least three more calibration gate openings.

- Step 6 - Plot a calibration curve of aggregate flow rate versus gate height.
- Step 7 - Fill the paver asphalt emulsion storage tank and put the pumping system on total recycle; determine the maximum pumping rate with both pumps. It should be 200+ gpm (760 l/min).
- Step 8 - Adjust pumps to a flow rate ~90% of maximum.
- Step 9 - Determine the aggregate flow rate required to produce an admix with kg/kg dry aggregate using the following formula:

$$A = E X_E P_A / X_A (1 - X_m)$$

where A = aggregate flow rate, lb/min kg/min

E = asphalt emulsion flow rate, gpm (l/min)

X_E = wt fraction asphalt in the emulsion

P_A = density of emulsion, lb/gal (g/ml)

X_A = weight of asphalt/weight dry aggregate in the seal (0.22)

X_m = wt fraction moisture in aggregate.

- Step 10 - Adjust the calibration gate height to give the required aggregate rate according to the calibration chart.
- Step 11 - Fill aggregate hopper on paver and pave a short test strip (~6 m long). This area should be separate from the tailings that are to be covered.
- Step 12 - Take a sample from the test plot and determine the asphalt content. Visually inspect the admix (see Testing and Quality Assurance Section for details).
- Step 13 - Based on the asphalt test results, adjust the pumping rate as follows:

$$E_N = 0.22 E_T / X_T$$

where E_N = the new asphalt emulsion flow rate, gpm (ℓ/min)

X_T = lb weight asphalt/lb weight dry aggregate in sample

E_T = asphalt emulsion flow rate during the test.

- Step 14 - If the sample is between 0.18 and 0.26 kg/kg dry aggregate, paving can begin after adjusting the asphalt emulsion pumping rate. If the sample is not in that range, repeat Steps 5, 6, and 7 after adjusting the asphalt emulsion flow rate.

Paving

The following steps outline the paving procedure:

- Step 1 - Set the screed for a width of 10 ft (3.0 m). With sloughing this should result in a paving width of ~12 ft (3.6 m).
- Step 2 - Calculate the operating speed for the cold mix paver using the following formula:

$$V = E/WU$$

where V = speed of cold mix paver (ft/min, m/min)

E = asphalt emulsion pumping rate (gal/min, ℓ/min)

W = paving width (12 ft, 3.6 m)

U = asphalt emulsion usage (0.83 gal/ft², 34 ℓ/m²)

This operating speed is only a guideline and should be adjusted during paving.

- Step 3 - If the paving base is flat (<2% slope), the paving can be done in any direction. For greater slopes, it is desirable to pave across the slope, beginning at the bottom and moving up the slope with each succeeding pass. In both of these modes, the paver can turn around at the end of each pass and pave in both directions. The paver can also pave up the slope; however, at the end of each pass, the machine must back all the way down to the starting point to begin paving again. An effective seal cannot be attained by paving on a down-grade, because the asphalt will run downhill ahead of the paver and the resulting seal will be too thin.

- Step 4 - One aggregate truck will be dumping into the paver hopper at all times during paving. Another truck will be loaded and ready to replace the truck dumping into the paver. A third truck will be loading.
- Step 5 - Two distributor trucks will be in operation to keep the bitumen tank on the paver full. After the distributor truck is empty, it will return to the asphalt tanker to refill. The distributor truck will be connected/disconnected to the paver without stopping the paving process.
- Step 6 - Several potential problems may be encountered in the field. The most common problem will probably be admix that is the wrong consistency, either too runny or too thick. When the admix is being applied properly, it will have the following characteristics: shiny brown color, mostly smooth and even surface with no uncoated aggregate visible, ~15-cm depth in the center of the pass and slight slumping at the edges of the pass; the admix will run ~2 ft out from the screed on the sides, and the seams will flow together with a minimum of handwork. If this is not the case, there are four primary causes: 1) admix does not have the correct composition (too much or too little asphalt); 2) the slope on the plot does not meet specifications, causing the admix to run more than is acceptable; 3) the set time of the admix is too long (admix will run too much) or too short (admix will set up too quickly and not flow); 4) the admix is not being properly mixed. When the paver is operating correctly the admix will cover 1/2 to 2/3 of the depth of the pug mill auger and will provide good mixing.

The admix will not be the correct thickness if the paving is too fast (admix is not deep enough) or too slow (admix is too thick). Lumps in the seal are usually caused by contamination of the admix. Sources of contamination include clumps of paving base, which may be

caused by the heavy equipment or picked up by asphalt on the wheels of the vehicles, and clumps of earthen material in the aggregate.

- Step 7 - Some handwork will be necessary for a good seal. This handwork will consist primarily of smoothing the seams and repairing holes or lumps caused by contamination. Seams are most easily done before the admix sets up. Lumps or holes can be repaired after setup.

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