Cost of Radon Barrier Systems for Uranium Mill Tailings

**E. G. Baker
J. N. Hartley**

August 1982

**Prepared for the U.S. Department of Energy
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SUMMARY

Earthen, asphalt, and multilayer covers can all provide significant reduction in the amount of radon gas exhaling from uranium mill tailings. All three types of covers were field tested in Grand Junction, Colorado during the summer of 1981. Four different 3m thick earthen covers were tested and cost an average of \$27/m². The least expensive earthen cover cost was about \$21/m². The asphalt cover system (6-7 cm of asphalt topped with 0.6m of overburden) cost about \$28/m². The four multilayer covers averaged \$57/m², but materials handling problems encountered during the test inflated this cost above what was anticipated and significant cost reductions should be possible. The least expensive multilayer cover cost \$43/m².

Based on the results of the Grand Junction field test we estimated the cost of covering the tailings from three high priority sites, Durango, Shiprock, and Salt Lake City (Vitro). The cost of a 3m earthen cover ranged from \$18-33/m² for the seven disposal sites (two or three at each location) studied. The cost of asphalt cover systems were \$23-28/m² and the multilayer cover costs were between \$31-36/m². The earthen cover costs are less than the Grand Junction field test cost primarily because cover material is available at or near most of the disposal sites selected. Earthen material was imported from 6-10 miles for the field test. Assuming more efficient utilization of materials significantly reduced the cost of the multilayer covers.

Several factors not yet completely defined will have a significant impact on the cost of all three systems. These include:

- location of the disposal site
- radon flux reduction required
- effectiveness of cover materials

A sensitivity analysis on a generic disposal site indicated that the asphalt and multilayer covers are most sensitive to thickness of the radon control layer and the cost of materials. The earthen cover is most sensitive to the amount of cover required and the disposal site location i.e., the availability of cover material near the site.

While there are significant cost differences between the three types of cover systems these cost differences are not nearly as significant when compared to the overall cost of remedial action. This indicates that in most instances the choice between cover systems should be based on the anticipated effectiveness and stability of the cover systems rather than on cost.

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INTRODUCTION

Radon gas exhaling from uranium mill tailings is considered a potential radiation health hazard if inhaled by persons near the tailings site. Numerous concepts are being advanced to stabilize uranium mill tailings located primarily in the western U.S. The Department of Energy's Uranium Mill Tailings Remedial Action Project (UMTRAP) Office contracted Pacific Northwest Laboratories (PNL) to evaluate radon barrier systems. This report deals specifically with the cost of three types of radon barrier systems, earthen covers, asphalt emulsion covers, and multilayer covers, which could meet standards proposed by the Environmental Protection Agency.

In the summer of 1981 PNL field tested these three radon barrier systems at the Grand Junction, Colorado tailings pile. We compiled the actual costs incurred for all three systems during the field test and they are presented in this report. PNL is currently monitoring the effectiveness of these cover systems. A more detailed discussion of the field test activities is given by Hartley and Gee (1981), Hartley, et al (1981), and Gee, et al (1981).

The cost of radon barrier systems will depend on several factors which are not yet completely defined, namely 1) the radon flux reduction which must be achieved, 2) the amount of cover material required to obtain the desired flux reduction, and 3) the exact location of the disposal sites. Despite these limitations, we believe valuable insights can be gained by comparing the cost of the three systems for several different tailings piles. Included in this report are cost estimates of the three different systems for three tailings piles designated high priority by the Department of Energy (DOE): Durango, Colorado; Shiprock, New Mexico; and Salt Lake City, Utah.

In addition, the report includes a sensitivity analysis of various factors which significantly effect the overall cost of the three systems. These analyses were based on a generic disposal site.

GRAND JUNCTION FIELD TEST COSTS

In the summer of 1981 PNL field tested earthen covers, asphalt covers, and multilayer covers at the Grand Junction, Colorado tailings pile. An overview of the Grand Junction field test site is illustrated in Figure 1. Four earthen cover systems were tested and consisted of:

- 1) 1.2 m (4 ft) of compacted Mancos shale covered with 1.8 m (6 ft) of adobe clay
- 2) 1.2 m (4 ft) of compacted local bentonite clay covered with 1.8 m (6 ft) of adobe clay
- 3) 1.2 m (4 ft) of compacted adobe clay covered with 1.8 m (6 ft) of adobe clay
- 4) 3 m (10 ft) of adobe clay dumped and spread

A total of 2500 m² was covered with 3 m of earthen material. The earthen materials were obtained from local borrow pits 10-16 km (6-10 mi) from the tailings pile. Material characteristics and other details on the earthen covers are given by Hartley and Gee (1981).

An area approximately 4000 m² was covered with 5-8 cm of asphalt and 0.6 m of overburden (adobe clay). In addition, approximately 900 m² was covered with asphalt but no overburden. The asphalt cover is described in more detail by Hartley, et al (1981).

A total of 3250 m² were covered with four different multilayer covers. The radon control layers for each cover were: 1) 15 cm gal/clay/rock barrier 2) 30 cm gel/clay/rock barrier 3) 30 cm bentonite/rock barrier 4) 40 cm bentonite/rock barrier. The radon control layers were then covered with a 23 cm-thick layer of washed rock, 10 cm of road base gravel, and 1 m of uncompacted adobe clay. These materials and layer configurations are described in detail by Gee, et al (1981).

We compiled the actual costs incurred during the field test for the three different systems and the results are shown in Table 1. These include all subcontractor costs and PNL costs incurred at the test site. PNL costs associated with engineering and planning the field test are not included. Materials were the major cost item for all three systems. A

FIGURE 1. Plan View of the 1981 PNL Cover System Field Test,
Grand Junction, CO.

TABLE 1. 1981 Grand Junction Field Test Costs

	Asphalt Covers \$	Earthen Covers \$	Multilayer Covers \$
Equipment(a)	27,640	9,620	48,760
Materials	85,920	41,800	108,490
Labor(b)	19,600	15,830	28,350
Total	\$133,160	67,250	185,600
Cost \$/m ²	\$27.20(c)	\$26.90	\$57.10

a) includes subcontractor labor

b) PNL labor plus a small amount of subcontractor labor

c) this cost would be about \$1/m² higher if all of the asphalt test area had been covered with overburden.

breakdown of the materials used during the field test and their cost is included in Appendix B. A list of the equipment used during the test is also included in Appendix B.

Table 2 shows the cost of the individual cover systems on a cost per square meter basis. The adobe clay earthen covers were the least expensive followed by the asphalt cover. The least expensive multilayer cover was the 15 cm gel cover.

The major cost item for the earthen covers was the cost of the earthen material. It was hauled in from 10-16 km (6-10 miles) to the site at a cost of \$3.90-5.90/m³ (\$3-4.5/cy). If a disposal site is chosen where sufficient cover material is available at or near the site this would reduce the cost of the cover by about \$5-8/m². More efficient utilization of equipment and labor could reduce the cost an additional \$2-3/m².

For earthen covers 1-3 only the first 1.2 m of the cover were compacted during the field test. Compaction densities ranged from 80% of proctor for the adobe clay to 93% of proctor for the mancos shale. If the entire 3 m were compacted to 95% of proctor 20-25% more earthen material would be required. The work required to compact the cover would also increase significantly. Overall, this would increase the cost of the cover by \$4-5/m². Earthen cover 4 was not compacted and was the least costly of the four earthen cover systems.

Table 2. Breakdown of Radon Barrier Systems Cost - Grand Junction Field Test

	3 m EARTHEN COVERS				ASPHALT	MULTILAYER COVERS			
	Mancos Shale	Local Bentonite	Adobe	Uncompacted Adobe	Asphalt	15 cm gel	30 cm gel	Bentonite/ Line 40 cm	Bentonite 30 cm
Equipment Usage	4.75	4.35	4.35	2.20	5.65	9.99	17.36	17.89	14.68
Radon Barrier Materials	--	--	--	--	13.70	14.30	28.60	25.89	17.31
Other Materials	--	--	--	--	0.93	5.12	5.12	5.12	5.12
Overburden	18.97	24.59	15.15	14.75	3.56	7.53	7.53	7.53	7.53
Labor & Misc.	7.16	7.16	7.16	3.58	4.00	6.49	9.32	12.31	9.94
TOTAL	30.48	36.10	26.66	20.53	27.84	43.40	68.00	68.80	54.60

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. We averaged approximately 57,000 L/day (15,000 gallons) of emulsion applied with a high of 79,000 L/day (21,000 gallons) during the field test. An application rate of 95,000 L/day (25,000 gallons) should be easily achieved in a full-scale operation. In addition, about 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, were not used resulting in extra costs. Overall, about $\$2\text{-}3/\text{m}^2$ could be saved in a fullscale operation.

On a cost basis only 10% of the materials delivered to the site for the earthen and asphalt covers were lost or wasted (not utilized in the cover itself). However, for the multilayer covers 30-40% of the materials were wasted. These losses resulting from stockpiling, mixing, restockpiling, application, and edge losses. A full-scale operation should reduce these losses significantly and reduce material costs. A full-scale operation would also reduce labor and equipment costs because of the reduced materials handling (less waste) and economies of scale. Overall, a reduction of $\$10/\text{m}^2$ or more may be possible for the 15 cm gel cover.

SITE SPECIFIC COST ESTIMATES

Three high priority uranium mill tailings sites, Durango, Shiprock, and Vitro, were selected to compare the costs of earthen, asphalt, and multilayer radon barrier systems. Ford, Bacon, and Davis identified several disposal locations for each mill tailings site in their engineering assessment of (inactive) uranium mill tailings (F,B,&D 1980 a,b,c). We selected two or three locations at each site for our evaluation. We selected the least expensive location as identified by F,B,&D and one or two other sites which had different characteristics (earthen material available at site, below grade disposal, imported cover material, above grade disposal, etc.). The location of the sites is shown in Figure 2. A more detailed description of these sites can be obtained from F,B,&D reports. The following words of caution were included in each disposal site assessment made by F,B,&D and applies to these cost studies as well:

"Although each alternate disposal site has specific and unique characteristics which were considered in estimating costs, great care must be exercised in the use of these site specific cost estimates since there is insufficient data and information to characterize the sites completely for estimating site development costs."

BASIS FOR COST ESTIMATES

To compare the cost of earthen, asphalt emulsion, and multilayer radon barrier systems only the costs associated with the cover itself were considered. Costs for hauling and placing the tailings as well as post treatment such as riprapping or vegetation were assumed to be equal for all types of cover. While this may not strictly be true, we feel the variations will be small in relation to the total cost of the cover systems. The basis for calculating the cost of each system and the assumptions used are discussed in the following sections.

Earthen Cover

The cost for earthen covers includes: (1) excavating the cover material either at the site or at a borrow some distance from the site, (2) stock-piling cover material (material excavated at the site), (3) hauling cover material from an off-site borrow (if necessary), and (4) placing the cover

FIGURE 2. Location of Potential Disposal Sites Near High Priority Western Tailings Piles.

material over the tailings and compacting to 90-95% proctor. Imported cover material was assumed to be free at the borrow site and we also assumed that borrow sites were already accessible by road. The availability of cover material was based on Ford, Bacon, & Davis' Engineering Assessment of Inactive Uranium Mill Tailings (1981, a,b,c). The depth of the cover material was set at 3 m.

Costs for the earthen cover system were based on various construction cost estimating handbooks (Bergert 1981; Richardson 1973; Engelsman 1982; Means 1981), discussions with contractors located near several tailings piles, and experience obtained from the 1981 Grand Junction field test.

Local contractors that were contacted to discuss earth moving costs in their area were:

- (1) Corn Construction, Grand Junction, CO
- (2) Nielsons, Cortez, CO (near Durango and Shiprock sites)
- (3) Mountain Gravel, Delores, CO (near Durango and Shiprock sites)
- (4) Don Arnold Construction, Grand Junction, CO

Cost estimates by local contractors generally agreed with those obtained from cost estimating handbooks. Several contractors were concerned about the availability of large quantities of cover material in the Durango and Shiprock areas. Local borrow pits are generally shallow and difficult to excavate.

Asphalt Cover

The cost of the asphalt cover is based primarily on the 1980 and 1981 Grand Junction field test data and on discussions with asphalt emulsion suppliers. The asphalt emulsion itself accounts for about 40% of the total cost so factors affecting the price and quantity required are particularly important.

The asphalt emulsion radon barrier system as laid down in Grand Junction consists of:

- 1) 10 cm (4 in) of 2 cm (3/4 in) gravel as a paving base
- 2) 34 $\pm$ (9.1 gal) of asphalt emulsion/m²
- 3) 104 kg (230 lb) concrete sand/m²
- 4) 0.6 m (2 ft) of earthen cover

This results in a 5-8 cm ($\sim 2-3$ in) asphalt seal containing 22 kg asphalt/100 kg of dry aggregate (concrete sand). This same system was used as a basis for the site specific cost estimates.

We estimate that for a full scale operation that about 95,000 liters (25,000 gal) per day of asphalt emulsion could be applied in an 8-hour day. This corresponds to about 2750 m²/day (29,400 ft²/day). Subcontractor costs were based on this paving rate and subcontractor charge out rates during the field test.

The cost of asphalt emulsion will have a significant impact on the cost of the asphalt cover. Discussions with ARMAK Research, McCook, Illinois and Petroleum Sciences, Inc., Spokane, Washington, indicated the price of asphalt emulsion such as the one we used for the field test (cationic medium-set (CMS-2) containing 63 wt% asphalt) is \$155-200/metric ton (\$0.15-\$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 cost estimates the delivered costs ranged from \$0.21 to \$0.33/l (\$0.80-\$1.25/ gal) depending on the location of the site.

Multilayer Cover

The cost of the multilayer cover is based primarily on Grand Junction field test data. We also talked to local contractors (see earthen covers) about materials availability and pugmill/mixer vendors about mixing costs. The multilayer cover chosen for these cost estimates is a 15 cm gel cover tested at the 1981 Grand Junction field tests. The 15 cm radon control barrier contains, on a weight basis: 75% road base gravel, 13% topsoil, 8% alum (aluminum sulfate), and 4% lime. The density of this layer is 2.0 Mg/m³ (125 lb/ft³). This is covered with 20 cm of washed rock, 10 cm of road base gravel, and 1 m of uncompacted overburden.

During the Grand Junction field test mixing of the radon control barrier materials was the most difficult task. A production rate of 700-900 metric tons per day was obtained with the gel mix. With a larger pugmill/mixer and more efficient operation we assumed a production rate of 2400 metric tons per day for the cost estimates. For all materials other than the overburden we assumed a 25% excess was required to cover materials handling losses.

DURANGO, COLORADO SITE

The two disposal sites evaluated were the Bodo Canyon site and the East Ridges Basin site. These two sites are both close to the tailings pile (6.1 km and 6.6 km) and were the least expensive of those identified by Ford, Bacon, & Davis (1981 a). These two sites also provide two different disposal approaches. The Bodo Canyon site is about 16 ha (40 acres) in size and has very shallow soils. A majority of the earthen cover materials would have to be imported from 4-6 km (3-4 miles) and the tailings disposal would be only partly below grade. The East Ridges Basin site is about 14 ha (35 acres) and all of the earthen cover material for a 3 m cover could be obtained from the site or from land immediately adjacent to the site. Tailings disposal would be below grade.

The estimated cost of earthen, asphalt, and multilayer radon barrier systems for the two disposal sites are shown in Tables 3,4, and 5. The cost of a 3 m of earthen cover is the least expensive cover system followed by the asphalt cover. The East Ridges Basin site has the lowest costs for earthen cover because of the availability of cover material at the site. East Ridges Basin site is also somewhat smaller than the Bodo Canyon site which reduces the overall cost for all three cover systems.

SHIPROCK, NEW MEXICO SITE

The two disposal sites studied for disposal of the tailings from the Shiprock tailings pile were Many Devils site and the Rattlesnake site. These were the two least expensive sites identified by Ford, Bacon, & Davis (1981 b).

The Many Devils site is 6.4 km (4 miles) from the tailings pile and covers approximately 32 ha (80 acres). The soils are only .25-.5 m (10-20 inches) deep on the site but the surrounding area should provide suitable cover materials (Ford, Bacon, & Davis 1981 b). We assumed that only 20% of the earthen cover required could be obtained at the site. The rest would have to be hauled 3.2 km (2 miles) for the 3 m cover.

Table 3. Cost of 3 m Earthen Cover Systems for Durango, CO. Site

Site	Cost \$1000 (1981)	
	<u>East Ridges Basin</u>	<u>Bodo Canyon</u>
1. Excavating and stockpiling	610	410
2. Hauling imported cover	--	1110
3. Placement and compaction	<u>920</u>	<u>690</u>
4. Total (1-3)	1530	2210
5. Engineering and Construction Management(a)	<u>460</u>	<u>330</u>
6. Total (4-5)	1990	2540
7. Contingency (30% of 6)	<u>600</u>	<u>760</u>
8. Total (6-7)	2590	3300
9. Cost \$/m ²	18.20	20.40

a) 30% of 4 excluding materials transportation costs.

Table 4. Cost of Asphalt Emulsion Cover System for Durango, CO. Site

Site	Cost \$1000 (1981)	
	<u>East Ridges Basin</u>	<u>Bodo Canyon</u>
1. Tailings stabilization	180	210
2. Application of asphalt seal	1910	2180
3. Overburden	<u>350</u>	<u>470</u>
4. Total (1-3)	2440	2860
5. Engineering and Construction Management(a)	<u>450</u>	<u>520</u>
6. Total (4-5)	2890	3380
7. Contingency (30% of 6)	<u>870</u>	<u>1010</u>
8. Total (6-7)	3750	4390
9. Cost \$/m ²	26.50	27.10

a) 30% of 4 excluding materials transportation costs.

Table 5. Cost of Multilayer Cover System for Durango, CO. Site

Site	Cost \$1000 (1981)	
	East Ridges Basin	Bodo Canyon
1. Radon control barrier	2050	2350
2. Capillary barrier/road base layer	590	680
3. Overburden	390	630
4. Total (1-3)	3030	3660
5. Engineering and Construction Management(a)	690	750
6. Total (4-5)	3720	4410
7. Contingency (30% of 6)	1110	1320
8. Total (6M)	4840	5730
9. Cost \$/m ²	\$35.60	\$34.50

a) 30% of 4 excluding materials transportation costs.

The Rattlesnake site is located about 8 miles west of Shiprock next to a 10 m high bluff. It will be necessary at this site to haul most of the overburden for the 3 m earthen cover from at least 5-10 km (3-6 miles). We assumed that only 20% of the earthen cover required could be obtained at the site. The rest would have to be transported an average 7.2 km (4.5 miles). The site is approximately 20 ha (50 acres).

The estimated cost of earthen asphalt, and multilayer radon barrier systems for the two disposal sites are shown in Table 6,7, and 8. The earthen cover is the least expensive at both sites followed by the asphalt cover.

VITRO SITE - SALT LAKE CITY, UTAH

The three sites evaluated for disposal of the Vitro tailings are a site 13 km (8 miles) north of Clive, Utah; Sager's Flats, 10 km (6 miles) east of Thompson, Utah; and the current location of the pile. The Clive, Utah site is one of three similar sites located about 100 miles west of Salt Lake City. It is a large depression (36 km², 4-5 m deep) with enough soil available at the site for a 3 m earthen cover (Ford, Bacon & Davis

Table 6. Cost of Earthen Cover Systems for Shiprock, NM. Site

Site	Cost \$1000 (1981)	
	<u>Many Devils</u>	<u>Rattlesnake</u>
1. Excavating and stockpiling	1090	680
2. Hauling imported cover	1380	1430
3. Placement and compaction	<u>1370</u>	<u>850</u>
4. Total (1-3)	3840	2960
5. Engineering and Construction Management(a)	<u>740</u>	<u>460</u>
6. Total (4-5)	4580	3420
7. Contingency (30% of 6)	<u>1370</u>	<u>1030</u>
8. Total (6-7)	5950	4450
9. Cost \$/m ²	18.40	22.00

a) 30% of 4 excluding materials transportation costs.

Table 7. Cost of Asphalt Emulsion Cover

Site	Cost \$1000 (1981)	
	<u>Many Devils</u>	<u>Rattlesnake</u>
1. Tailings stabilization	410	260
2. Application of asphalt seal	4360	2720
3. Overburden	<u>840</u>	<u>640</u>
4. Total (1-3)	5610	3620
5. Engineering and Construction Management(a)	<u>990</u>	<u>610</u>
6. Total (4-5)	6600	4230
7. Contingency (30% of 6)	<u>1980</u>	<u>1270</u>
8. Total (6-7)	8580	5500
9. Cost \$/m ²	26.50	27.20

a) 30% of 4 excluding materials transportation costs.

1981 c). We assumed the size of the actual disposal area to be 26 ha (65 acres).

The Sager's Flat site is 354 km (220 miles) southeast of the Vitro site. Stabilization with an earthen cover system will be more difficult than at the Clive site. It probably would not be possible to excavate to 3 m depth to dispose of the tailings below grade and allow for the required amount of cover material (Ford, Bacon, & Davis 1981 c). We assumed that 50% of the cover material for a 3 m cover could be excavated at the site and the rest would have to be hauled an average of 16 km (10 miles). We assumed the size of the site to be covered was 28 ha (70 acres).

The tailings currently occupy 46 ha (110 acres) at the Vitro site in Salt Lake City. Earthen cover would have to be imported from 24-32 km (15-20 miles) (F,B,&D 1980 c). Because of the availability of materials for the asphalt and multilayer covers in the Salt Lake area stabilization in place provides a significant cost advantage to asphalt and multilayer covers.

Table 8. Cost of Multilayer Cover for Shiprock, NM. Site

Site	Cost \$1000 (1981)	
	<u>Many Devils</u>	<u>Rattlesnake</u>
1. Radon control barrier	4780	2990
2. Capillary barrier/road base layer	1340	840
3. Overburden	980	600
4. Total (1-3)	7100	4430
5. Engineering and Construction Management(a)	1500	940
6. Total (4-5)	8600	5370
7. Contingency (30% of 6)	2600	1610
8. Total (6-7)	11200	6980
9. Cost \$/m ²	\$35.00	\$34.90

a) 30% of 4 excluding materials transportation costs.

Tables 9,10 and 11 show the estimated cost of earthen, asphalt, and multilayer radon barrier systems for the three disposal sites. The cost of the 3 m earthen cover is the least expensive cover at the Clive site. However, at the Sager's Flat site the cost difference between the earthen cover and the asphalt cover is much smaller because of the long haul distance assumed for the earthen material. If the tailings are stabilized in place the asphalt cover is significantly less expensive than the 3 m earthen cover and the multilayer cover is only slightly more than the earthen cover.

CONCLUSIONS

The cost figures are quite similar for all three disposal sites. The asphalt and multilayer cover costs are less sensitive to site selection than the earthen covers. Transportation costs for materials for the asphalt and multilayer covers are affected by site selection, but they do not significantly affect the overall cost of the cover. However, for the earthen cover systems the cost of hauling cover material has a big impact on the final cost of the cover. Except for the Sager's Flat site (Vitro) and stabilization of the Vitro tailings in place, all of the disposal sites identified by Ford, Bacon and Davis had enough earthen material at or near the site for a 3 m cover. If a disposal site is chosen where earthen material must be imported from a significant distance (8 km or more) the cost of earthen and asphalt covers will be similar as was the case with the Grand Junction field test.

Table 9. Cost of Earthen Cover Systems for Salt Lake City (Vitro Site)

Site	Cost \$1000 (1981)		
	<u>Clive</u>	<u>Sager's Flat</u>	<u>In Place</u>
1. Excavating and stockpiling	1380	1140	1900
2. Hauling imported cover	--	1980	7310
3. Placement and compaction	1120	1290	2060
4. Total (1-3)	2500	4410	10370
5. Engineering and Construction Management(a)	750	730	920
6. Total (4-5)	3250	5140	11290
7. Contingency (30% of 6)	975	1540	3390
8. Total (6-7)	4230	6680	14680
9. Cost \$/m ²	\$16.10	\$23.60	\$33.00

a) 30% of 4 excluding materials transportation costs.

Table 10. Cost of Asphalt Emulsion Cover for Salt Lake City (Vitro Site)

Site	Cost \$1000 (1981)		
	<u>Clive</u>	<u>Sager's Flat</u>	<u>In Place</u>
1. Tailings stabilization	340	360	540
2. Application of asphalt seal	3025	3820	3970
3. Earthen cover	570	610	2300
4. Total (1-3)	3940	4790	6810
5. Engineering and Construction Management(a)	800	880	1590
6. Total (4-5)	4740	5670	8400
7. Contingency (30% of 6)	1420	1700	2520
8. Total (6-7)	6160	7370	10920
9. Cost \$/m ²	\$23.40	\$26.00	\$24.50

a) 30% of 4 excluding materials transportation costs.

Table 11. Cost of Multilayer Cover System for Salt Lake City (Vitro Site)

Site	Cost \$1000 (1981)		
	<u>Clive</u>	<u>Sager's Flat</u>	<u>In Place</u>
1. Radon control barriers	3220	3730	5050
2. Capillary barriers/road base layer	1100	1190	1670
3. Overburden	<u>740</u>	<u>760</u>	<u>3450</u>
4. Total (1-3)	5060	5680	10170
5. Engineering and Construction Management(a)	<u>1240</u>	<u>1330</u>	<u>2180</u>
6. Total (4-5)	6300	7010	12350
7. Contingency (30% of 6)	<u>1890</u>	<u>2100</u>	<u>3710</u>
8. Total (6-7)	8190	9110	16050
9. Cost \$/m ²	\$31.10	\$32.10	\$36.10

a) 30% of 4 excluding transportation costs.

SENSITIVITY ANALYSIS

Several factors could significantly affect the cost of all three radon barrier systems. These include:

- The required thickness of each cover system
- The location of the site. This determines the transportation costs for the materials. It is particularly significant for the earthen covers.
- The purchased cost of materials. This is most significant for the asphalt and multilayer covers.

Figure 3 shows the effect of earthen cover depth and the average haul distance for cover material on the cost of earthen radon barrier systems. The amount of earthen cover will depend on the flux reduction required and the diffusion coefficient of the cover material. The availability of cover will depend on the final site selection.

Reducing the thickness of the asphalt emulsion seal will significantly reduce the cost as shown in Figure 4. The cold mix paver may not be capable of applying a thinner seal, however, a slurry seal machine may be capable of applying an effective seal 3 cm (1.2 inches) thick (Asphalt Institute 1979). Discussions with suppliers of asphalt and asphalt emulsion indicated the price of asphalt will probably remain stable and possibly drop in the short term. In the long term, prices will probably increase somewhat faster than inflation.

As indicated previously, the cost of materials for the radon barrier layer is the major cost item for the multilayer covers. Figure 5 shows the effect of a 25% increase and decrease in the cost of materials. This could be an increase/decrease in the cost per unit or an increase/decrease in the quantity of materials required. For example, locally available alum waste from municipal sewage treatment plants could reduce the cost of the radon control layer by 25%.

Table 12 shows the cost of all three systems as a percentage of the total remedial action costs estimated by Ford, Bacon, & Davis (1981 a,b,c). The total cost of remedial action includes the cost of removal of the tailings

FIGURE 3. Effect of Cover Depth and Haul Distance on the Cost of Earthen Covers.

FIGURE 4. Effect of Asphalt Emulsion Cost and Seal Thickness on the Cost of Asphalt Radon Barrier.

Table 12. Cost of Radon Barrier Systems as a Percentage of Total Remedial Action Costs

	Cost - \$Millions (1981)				
	<u>Durango</u>	<u>Shiprock</u>		<u>Vitro</u>	
	<u>Bodo Canyon</u>	<u>Many Devils</u>	<u>Rattle-Snake</u>	<u>Clive</u>	<u>In Place</u>
Total Cost of Remedial Action ^(a) (F,B,&D 1981 a,b,c)	22.6	27.4	29.3	88.3	38.9
Cost of 3 m Earthen Cover	3.3	6.0	4.5	4.2	14.7
% of Total Cost	15	22	15	5	38
Cost of Asphalt Emulsion Cover	4.4	8.6	5.5	6.2	10.9
% of Total Cost	19	31	19	7	28
Cost of 15 cm Gel Multilayer Cover	5.7	11.2	7.0	8.2	16.1
% of Total Cost	27	41	24	9	41

(a) Assumes a 7% escalation from 1980 dollars to 1981 dollars.

This indicates the choice of cover system at many sites should be based primarily on cover effectiveness and anticipated long term stability rather than cost. In some instances, however, the location of the disposal site will favor one cover system over the others.

FIGURE 5. Effect of Materials Cost and Radon Barrier Thickness on the Cost of Multilayer Covers.

Figure 5. Effect of Material Cost and Radon Control Layer Thickness on the Cost of Radon Control.

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APPENDIX A
PROCEDURES AND EQUIPMENT FOR APPLYING
RADON BARRIER SYSTEMS

APPENDIX A Procedures and Equipment for Applying Radon Barrier Systems

This appendix describes the methods and equipment used at Grand Junction to apply the test covers. In some cases other equipment would be more appropriate for a full-scale operation so the cost estimates for Durango, Shiprock, and Vitro are not necessarily based on the same procedures and equipment used at Grand Junction. Discussions with contractors and construction handbooks were used along with our experience with the field test to select the most appropriate methods of applying the cover systems. These methods are also discussed here along with other alternatives that may also be cost effective.

Earthen Covers

A Caterpillar 980 wheel loader was used to excavate the earthen material used in the field test. For a more compacted borrow a crawler loader could also be used. For shallow borrows (less than 2 m) an elevating scaper might be the best choice. For the cost studies a crawler loader with a 2.1 m^3 (2.75 cy) bucket capacity was used.

Figure A-1 shows one of the trucks used to haul cover to the Grand Junction test site. These $15\text{--}23 \text{ m}^3$ (20-30 cy), rear-dump, semi-trailer tractor combinations offer a significant cost advantage over standard 7.7 m (10 cy) dump trucks particularly for long hauls.

At the field test we used a John Deere 8630 wheel-tractor (Figure A-2) to spread the earthen material in 15-20 cm (6-8 in) lifts. A distribution water truck and a Bomag BW 210 PD sheepsfoot roller (Figure A-3) were used for compaction. The cost estimates are based on a 16.8 m^3 (22 cy) elevating scraper (Figure A-4) and a 195 h.p. dozer (Figure A-5) to spread the earthen material and a water truck and a double 5x5 sheepsfoot roller for compaction.

Asphalt Emulsion Cover

At the Grand Junction field test a Model 701 Midland Mix-Paver was used to apply the asphalt emulsion seal. The paver is shown in Figure A-6. Dump trucks (10 cy) were used to keep the paver supplied with aggregate (see Figure A-6). A wheel loader was used to load the trucks from the aggregate stockpile. Asphalt emulsion was off-loaded from 6500 gallon insulated trailers to a distributor truck which supplied the paver with emulsion on the run.

FIGURE A-1 Kenworth 23 m³ Rear-Dump, Semi-Trailer and Tractor

FIGURE A-2 John Deere 8630 Wheel Tractor

FIGURE A-3 Bomag BW210PD Sheepsfoot Roller

FIGURE A-4 Allis Chalmers 260E Elevating Scraper

FIGURE A-5 Allis Chalmers HD-16 Crawler Dozer

FIGURE A-6 Midland 701 Cold Mix Paver

After the asphalt-emulsion seal had dried a Bomag BW 2204 vibratory tandem roller shown in Figure A-7 was used to compact the seal. The 0.6 m of earthen cover was placed over the seal in much the same manner as the 3 m earthen cover was applied.

Another possibility for applying the asphalt-emulsion seal is a slurry-seal machine. This machine is a self-contained, continuous-flow mixing unit. Application of the seal would be done in much the same manner as with the mix-paver.

Multilayer Covers

Raw materials for the radon control layer were stockpiled at the Grand Junction test site and then mixed in a Calenco Model 30 TP 14H pugmill shown in Figure A-8. The unit was rated at 300 t/hr. Front-end loaders transported the materials from the stockpiles to the pugmill and 7.7 m^3 (10 cy) dump trucks hauled the mixed material to nearby stockpiles. A 7600 water truck supplied the necessary water to the pugmill. An 11 m^3 (14.6 cy) elevating scraper similar to the one shown in Figure A-4 was used to spread the material on the test plot in 7-15 cm (3-6 in) lifts. A water truck, a Bomag BW 210 PD sheepfoot roller, (Figure A-3) and a Bomag BN 220A vibratory smooth-drum roller (Figure A-7) were used for compaction. The washed rock, roadbase, and overburden were all hauled to the site with 23 m^3 (30 cy) trucks (Figure A-1) and spread with a John Deere 8630 wheel tractor (Figure A-2). A similar procedure was used for the cost estimates although larger equipment was used to take advantage of economies of scale.

FIGURE A-7 Bomag BW2204 Vibratory Tandem Roller

FIGURE A-8 Calenco 30TP 14H Pugmill

APPENDIX B

MATERIALS AND EQUIPMENT COST BREAKDOWN

1981 GRAND JUNCTION FIELD TEST

Materials Cost Breakdown - 1981 Grand Junction Field Test

Earthen Covers

	<u>No. of Units</u>	<u>Cost/Unit(a)</u>	<u>Total Cost</u>
Mancos Shale	1900 c.y.	\$3.00	\$ 5,700
Adobe Clay	9000 c.y.	\$3.00	\$27,000
Bentonite	2025 c.y.	\$4.50	\$ 9,100
Total			\$41,800

Asphalt Emulsion Cover

	<u>No. of Units</u>	<u>Cost/Unit</u>	<u>Total Cost</u>
3/4" Road Base Gravel	573 c.y.	\$ 7.40	\$ 3,700
Concrete Sand	631 c.y.	\$11.45	\$ 7,224
Asphalt	45,000 gallons	\$ 1.35	\$60,750
Adobe Clay (Overburden)	4750 c.y.	\$ 3.00	\$14,250
Total			\$85,924

Multilayer Covers

	<u>No. of Units</u>	<u>Cost/Unit</u>	<u>Total Cost</u>
3/4" Road Base Gravel	3513 c.y.	\$7.00	\$25,993
Washed Rock	1280 c.y.	\$7.85	\$ 6,036
Adobe Clay (Overburden)	8160 c.y.	\$3.00	\$24,480
Alum	100 T	\$215.46	\$21,546
Lime	80 T	\$133.15	\$10,652
Bentonite	182 T	\$87.36	\$15,900
Miscellaneous			\$ 3,883
Total			\$108,490

a) cost delivered to the site

Metric Conversions - 1.33 c.y. = 1 m³
 1 gallon = 3.785 L
 1.1 T = 1.0 t (metric ton)

Equipment Cost Breakdown - 1981 Grand Junction Field Test

<u>Earthen Cover System</u>		<u>Total Cost \$</u>
1. Sheepfoot roller	- Bomag BW 210PD - \$3500/month	3563
2. Dozer + operator	- JD 8630 - \$45/hr	450
3. Paddle-Wheel scraper + operator	- JD E0866 - 11 m ³ - \$65/hr	650
4. Grader + operator	- \$50/hr	239
5. Water truck + operator	- 7600 & - \$35/hr	4298
6. Tandem vibratory roller	- Bomay BW 220A	417
7. Tractor/Trailer	- Kenworth - 23 m ³ - \$50/hr	*
Total		<hr/> \$9617

* cost included in cost of earthen material.

Equipment Cost Breakdown - 1981 Grand Junction Field Test

<u>Asphalt Emulsion System</u>		<u>Total Cost \$</u>
1. Cold mix-paver + 2 operators	- Midland 701 - \$10,500 + \$1500/day	16,815
2. Vibratory tandem roller	- Bomay BW 220A - \$3500/month	3,753
3. Front-end loaders + operator	- 2 m ³ - \$45/hr	1,755
4. Grader + operator	- \$50/hr	486
5. Dump trucks + operator	- 7.7 m ³ - \$30/hr	2,070
6. Water truck + operator	- 7600 l - \$35/hr	2,761
7. Asphalt tankers	- 24,000 l	*
Total		<hr/> \$27,640

* included in the cost of the asphalt.

Equipment Cost Breakdown - 1981 Grand Junction Field Test

<u>Multilayer Cover Systems</u>		<u>Total Cost \$</u>
1. Roller/Compactors Sheepsfoot Tandem-vibratory	- Bomag BW 210PD - Bomag BW 220A - Each \$3500/month	7,733
2. Front-end loaders	- 2 m ³ - \$45/hr	3,692
3. Pugmill	- Calenco 30TP 14H - 300 mt/hr - \$15K/week	20,545
4. Dump trucks	- 7.7 m ³ - \$30/hr	4,274
5. Water truck	- 7600 l - \$35/hr	7,402
6. Paddle-wheel scraper	- John Deere E0866 - 11 m ³ - \$65/hr	1,690
7. Dozer	- John Deere 8630 - 4m dozer blade - 4.75m backblade - \$45/hr	1,395
8. Backhoe	- \$50/hr	1,300
9. Grader	- \$47/hr	680
Total		<hr/> \$48,751

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