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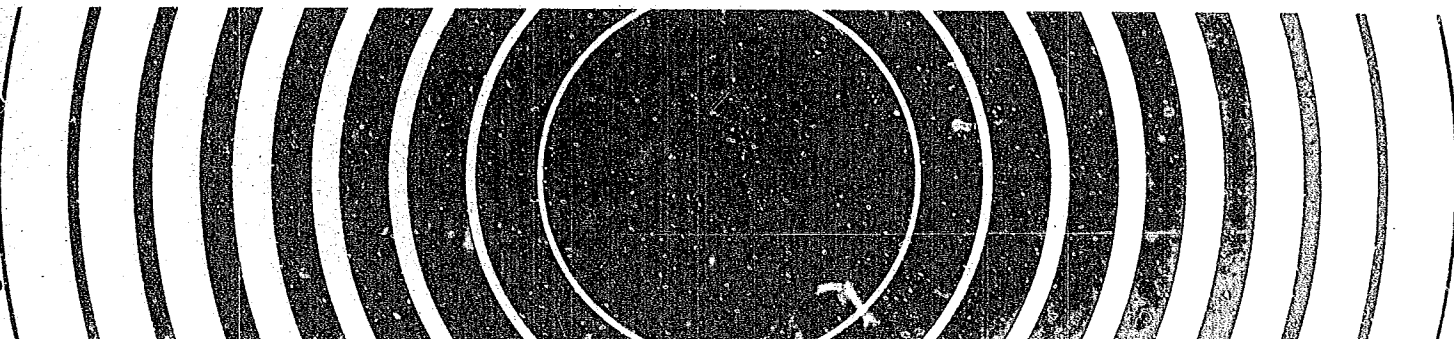
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Chapter 5: URANIUM MINES

5.1 General Description

In uranium mining operations, ore is removed from the ground in concentrations of 0.1 to 0.2 percent U_3O_8 or 280 to 560 microcuries of uranium-238 per metric ton of ore. Since the uranium-238 in the ore is normally present in secular equilibrium with its daughter products, these ores also contain equal amounts of each member of the uranium-238 decay series.

After mining, the ores are shipped to a uranium mill to separate the uranium. Radioactive emissions to air from uranium mines and mills consist of radionuclide bearing dust and radon-222 gas.

Uranium is mined in both open pit and underground mines. In 1982 there were 139 underground and 24 open pit uranium mines in operation in the United States (Table 5-1). These mines accounted for about 75 percent of the uranium produced (DOE83).

Table 5-1. Distribution of 1982 U_3O_8 production by mining method (DOE83)

Source	Number	Tons U_3O_8 (a)	Percent of total
Underground mines	139	6,200	46
Open pit mines	24	3,900	29
Solution Mining (In-Situ)	18	1,500	11
Others: heap-leach, mine water, byproduct, and low-grade stockpiles	15	1,800	14
Total	196	13,400	100

(a) short tons

In recent years in-situ solution mining has been more widely used; this method is expected to increase in future years. During 1982 this method accounted for 11 percent of the uranium mined in the United States. The radioactive emissions from this source are small compared to the other sources.

Table 5-2 indicates that at present all uranium is mined in the western United States, mostly in the states of New Mexico, Wyoming, and Texas. Exploration for uranium is being conducted, however, in the eastern and midwestern parts of the United States.

Table 5-2. Distribution of 1982 U₃O₈ production by State (DOE83)

State	U ₃ O ₈ (Short tons)	Percent of total
New Mexico	3,800	28
Wyoming	2,700	20
Texas	2,200	17
Arizona, Colorado, Florida, Idaho, Utah, & Washington	4,700	35
Total	13,400	100

Major publicly-held corporations account for a large share of ownership in the uranium industry. The industry grew rapidly in the early and mid-1970's, stimulated by expectations of rapid increases in demand. However, the expectations were too optimistic with supply outstripping demand. The result was an economic slump for the industry. The industry is now faced with excess capacity, large inventories, lower-than-expected demand, and the potential for increased competition from imports (EPA83a).

5.2 Process Description

Underground Mining

Underground uranium mining is usually carried out using a modified room and pillar method. In this method, a large diameter main entry shaft is drilled to a level below the ore body. A haulage way is then

established underneath the ore body. Vertical raises are driven up from the haulage way to the ore body. Development drifts are driven along the base of the ore body connecting with the vertical raises. Mined ore is hauled along the development drifts to the vertical raises and gravity fed to the haulage way for transport to the main shaft for hoisting to the surface.

Figure 5-1 is an example of an underground mining operation. Ventilation shafts are installed at appropriate distances along the ore body. Typical ventilation flow rates are on the order of 200,000 cfm. The principal radioactive effluent in the mine ventilation air is radon-222 which is released during mining operations. Additional radon-222 and particulate (uranium and its decay products) emissions result from surface operations at the underground mine.

Surface Mining

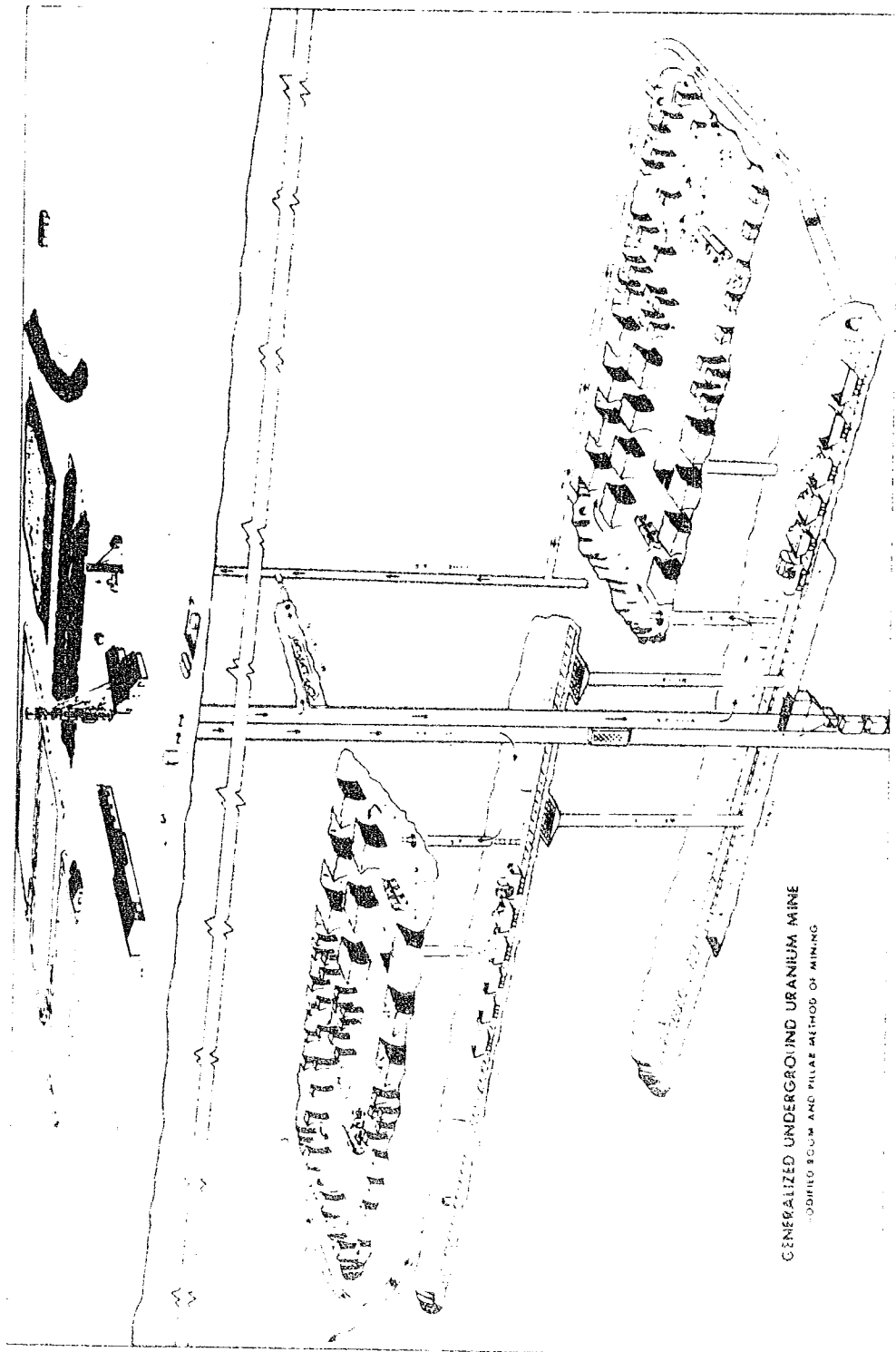
Open pit mining usually is carried out by excavating a series of pits in sequence. The topsoil and overburden are removed from above the ore zone and stockpiled in separate piles for use in future reclamation operations. The uranium ore is removed from the exposed ore zone and stockpiled for transport to a uranium mill. Ore stockpiles range in size up to several hundred thousand metric tons of ore. During the mining of the uranium ore, low grade waste rock is also removed from the pits and stored in a waste stockpile for possible future use.

Figure 5-2 is an example of an open pit mining operation. As the mining progresses, mining and reclamation operations take place simultaneously--pits are mined in sequence, and the mined-out pits are reclaimed by backfilling with overburden and topsoil. In some cases, the last of the open pits in a mining operation are not backfilled but are allowed to fill with water, forming a lake. Radioactive emissions from open pit mining operations are radon-222 gas and fugitive dust containing uranium and its decay products.

In-Situ Mining

In this method, a leaching solution is injected through wells into the uranium-bearing ore body to dissolve the uranium. Production wells bring the uranium-bearing solution to the surface where the uranium is extracted. The solution (lixiviant) can be recovered and reused.

Radon-222 gas is emitted from the processing operations and waste impoundments. With solution mining, less than 5 percent of the radium from an ore body is brought to the surface (NRC80). Consequently, the amount of radon released is considerably less than that from conventional mining. The major sources of radon are the surge ponds, enclosed surge tanks, inplant surge tanks, and absorption columns (Br81). It is estimated that the radon released is about 19 percent of the amount released from a conventional uranium mill (Bra81).



GENERALIZED UNDERGROUND URANIUM MINE
 (DOTTED SCUM AND PILLAR METHOD OF MINING)

Figure 5-1. An underground uranium mining operation.

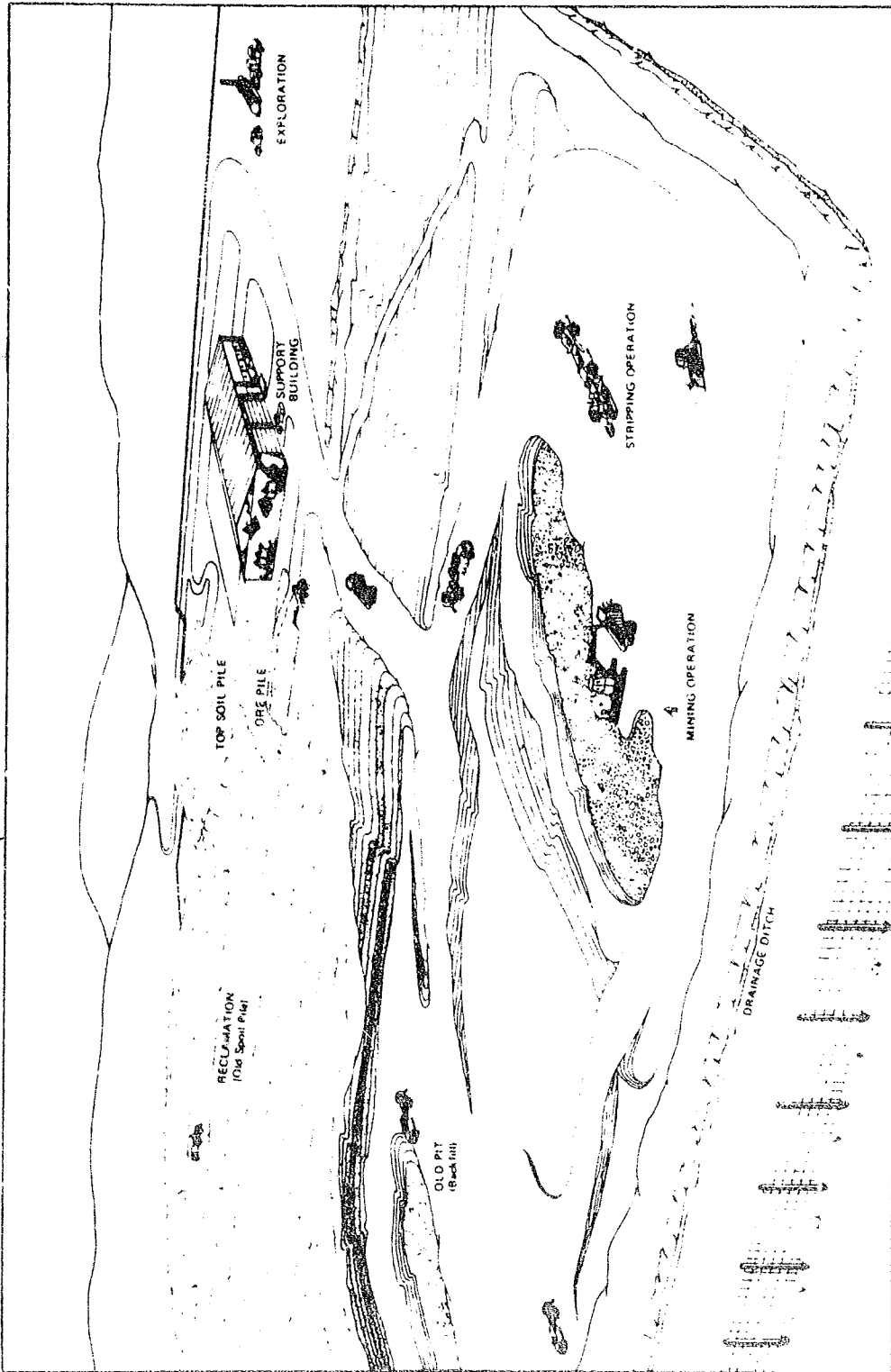


Figure 5-2. An open pit uranium mining operation.

A small amount of radon is released from the waste impoundments used to store contaminated liquids from the operation. Some examples of solid wastes (EPA83b) that might be generated by the alkaline leach in-situ process are:

- (1) Materials filtered from the lixiviant line.
- (2) Sediments from the surge tanks.
- (3) Calcium carbonate from the calcium control unit.
- (4) Barium sulfate from the cleanup of the elution/precipitation circuit of the recovery process.
- (5) Materials deposited in the evaporation ponds.
- (6) Drill hole residues.
- (7) Solids from aquifer restoration.

EPA has previously evaluated radionuclide emissions from uranium mining activities (EPA79, EPA83b). These evaluations indicate that underground uranium mining releases the largest quantities of radon-222 to air and results in the most significant health impacts when compared to other mining methods. Because of the lower amounts of radon released from surface mines, in-situ solution mining, and other mining methods, the potential health impact of underground uranium mining is of the most concern and therefore, Sections 5.3 through 5.8 of this chapter deal only with underground uranium mines.

5.3 Control Technology

Several methods to control radon emissions from underground uranium mines have been evaluated. These are: 1) use of sealant coating on exposed ore surfaces; 2) bulkheading of worked-out areas; 3) activated carbon adsorption of radon from contaminated mine air; 4) mine pressurization; and 5) miscellaneous technologies.

Sealant Coating

One method for controlling radon in an underground uranium mine is to prevent radon from entering the mine air by sealing exposed surfaces. A summary of field tests and a review of the literature on this subject performed for EPA (Ko80) is summarized as follows:

1) Under laboratory conditions sealants are very effective in attenuating radon emissions from ore surfaces, but in an actual mine application, the presence of "pinholes" and the difficulty of applying a perfect coating on a mine wall or ceiling surface reduces the effectiveness of these sealants considerably.

2) In field tests a three-coat system of HydroEpoxy 156 and HydroEpoxy 300, preceded by shotcrete base coating, was found to be effective (50 to 75 percent radon stoppage). For the theoretical mine, the sealant probably would be 60 percent effective with an eight-month lifetime.

3) The amount of sealants used varied considerably for different mines. Kown and his associates (Ko80) chose the following amounts for their study which were greater than other studies on this subject.

Shotcrete	-	909 gal per 1000 ft ²
HydroEpoxy 156	-	18 gal per 1000 ft ²
HydroEpoxy 300	-	32 gal per 1000 ft ²

4) The sealant coating applied to drifts of an underground mine has a limited life of about eight months because the drift area is mined after pillars are extracted in a room-and-pillar stope mine.

5) An asphalt emulsion sealant has been tested in the laboratory and on tailing piles and is found to be an effective, inexpensive sealant. However, it has not yet been tested in an underground mine atmosphere.

The cost of coating 530,000 ft² of drift surfaces in the mine was \$348,100 (\$1.45 per ton of ore removed). The floors were not considered to be coated because ore loaders will destroy the coating on the semiconsolidated muck. The three sealants were applied every two months. Cost estimates of other sealants range from \$0.30 to \$1.10 per square foot (Fr81) which is comparable to the cost estimates (\$0.66 per square foot) of the sealants used in this study. Because of its high cost, the Bureau of Mines feels that sealants may only be used economically in shops, lunchrooms, and possibly high-emanating areas in intake airways (Frc83).

A recent study by Battelle (B184) of 11 mines shows an average cost of \$5.80 per ton of ore mined (\$0.34 per square foot) if 80 percent of the surface is sealed. This EPA-sponsored study has shown that sealants could reduce the radon emanation from the active stopes of the mines by 23 percent. If the total mine is included (25 extracted stopes), only 11 percent of the radon was reduced. This second figure should be used when determining the amount of radon released from the mine.

Other studies by the Bureau of Mines (Fra81) have shown that 50 to 75 percent of the radon can be retained in the rock by sealants. The study by Battelle (B184) shows that a 56 percent reduction in radon emissions can be achieved by applying sealant to 80 percent of the mine surfaces.

Bulkheading

Bulkheading of mined-out areas, such as extracted stopes, is the most common radon control method currently practiced in underground mines (Ko80). In general, it is used to isolate worked-out areas or

stopes from workers so that the radon concentrations in the working areas of the mine will be lower. If the bulkhead is air tight, the radon behind the barrier will decay to innocuous levels. However, all bulkheads leak to some extent, and usually a small 3- to 6-inch ventilation pipe is used as a bleeder pipe to provide negative pressure in the extracted stope (Fra81) and to allow the contaminated air to be diverted to the ventilation system. A small fan may be required to maintain the negative pressure. Ideally, only 10 percent of the air behind the bulkhead would be diverted to the outside atmosphere. This air stream can also be connected to an activated carbon filter or trap to reduce concentrations further.

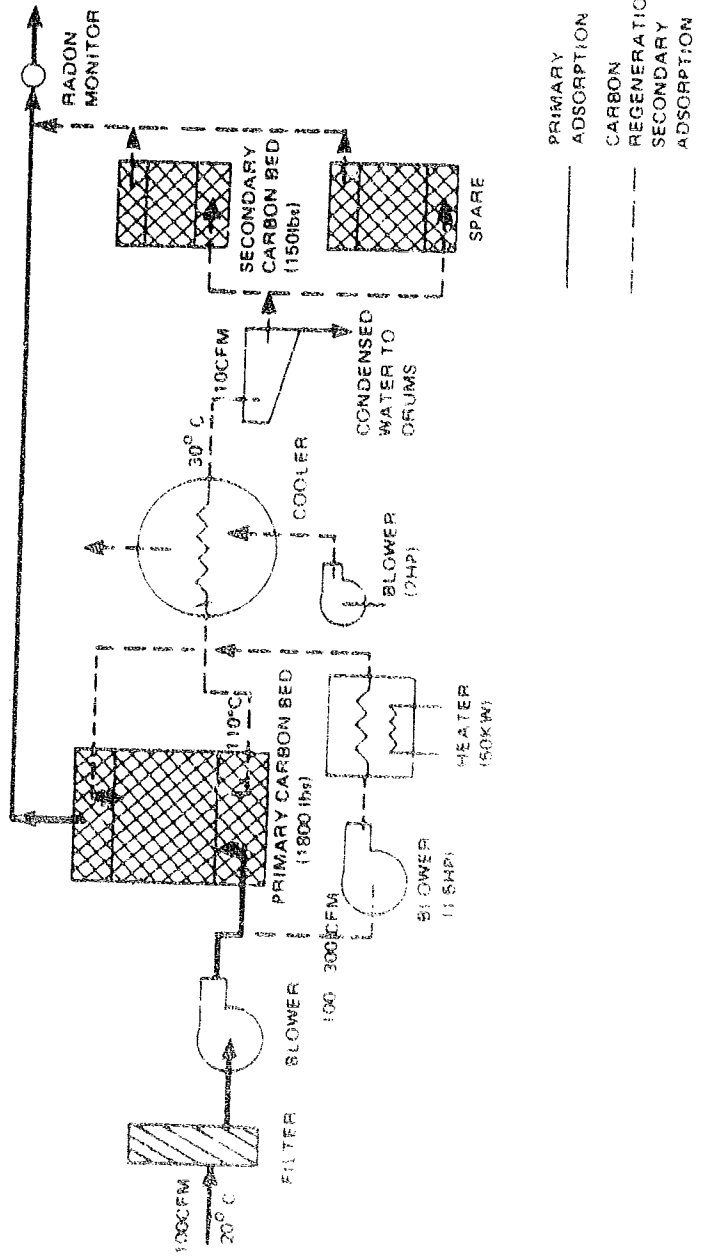
In an EPA study (Ko80) it was assumed that 12.5 stopes per year would be sealed using 100 bulkheads. The cost for material, labor, and maintenance was estimated to be \$80,400 or \$0.34 per ton of ore removed. It was also assumed that a six-inch pipe provided a 100 cfm bleeding rate from each bulkheaded area. In a Battelle study (B184) the average cost to bulkhead 80 percent of the mine at 13 sites was only \$0.08 per ton of ore. Up to 10 bulkheads in each mine were used in making these estimates.

An estimate of the effectiveness of reducing radon by this system was made using many crude assumptions. For the total mine, bulkheading was estimated to achieve about a 14 percent reduction in radon emissions (Ko80). A preliminary study conducted by Battelle on an actual mine indicated that a radon reduction of 35 percent could be obtained by using bulkheads (Dra80). Using bulkheads extensively in a mine can reduce radon emissions up to 60 percent (B184).

Radon Adsorption on Activated Carbon

Leakage of high radon concentrations through bulkheads used to control radon concentrations in mines is another problem. One method to relieve this problem is to insert a small bleeder pipe in the bulkhead to provide negative pressure within the enclosed area behind the bulkhead. This bleeder pipe is usually connected to the exhaust ventilation system. Although this may prevent exposure to the workers, the radon emissions to the environment may still be high. An activated carbon adsorption system may be attached to the radon effluent pipe before releasing this air to the exhaust ventilation system (Ko80).

An effective radon control system for the bleeder pipe is under study. The system chosen by investigators in an EPA study is shown in Figure 5-3. It consists of two carbon adsorption columns in series. The flow from the bleeder pipe is filtered to remove dust particles and radon daughter products. The radon is then adsorbed by the carbon column. The carbon column is regenerated periodically with hot air. The contaminated air from the regeneration is sent through a second carbon column to again adsorb the radon gas. A second fan may be required in the second column due to blinding of the fan.



Radon removal from mine air by carbon adsorption.

In evaluating control technology in a model mine, EPA (Ko80) found that an average of 12.5 activated carbon systems must be installed each year to treat the contaminated air from the stopes sealed by the bulkheads. The capital and operating costs for each unit are as follows:

Capital Cost of Each Unit

Major equipment	\$22,000
Auxiliaries & Installation	<u>\$11,000</u>
Total	\$33,000

Annualized Cost of Each Unit

Material (carbon, filters, piping)	\$ 1,000
Utilities (25,000 kwh @ 4¢/kwh)	\$ 1,000
Labor (0.25 person-year)	\$ 8,000
Amortizing (an avq. 5-year life at 10 percent interest)	<u>\$ 8,700</u>
Total	\$18,700

Assuming the lifetime of each unit is 5 years and 12.5 units per year are needed, the cost over five years would be \$1,037,500 or \$0.86 per ton of ore mined. The carbon system was assumed to be 95 percent efficient in removing radon.

The effectiveness of the entire system, including bulkheading and carbon traps, was estimated to be 49 percent. A study by Battelle (Dra80) estimates a 45-68 percent effectiveness, using absolute sorption traps in combination with bulkheading. The total cost for bulkheading and carbon traps would be \$1.20 per ton of ore mined for 100 bulkheads. In the study by Battelle (Bl84) the average cost to bulkhead with a carbon trap at 13 mines was \$0.11 per ton of ore with an efficiency of 80 percent. Up to 10 bulkheads in each mine were used for their estimate.

There are some definite disadvantages to the carbon adsorption system. Skilled operators, usually not available in mining communities, are necessary to operate and maintain the system. Safety problems to the miners are possible due to interrupted electrical service or system malfunction. Excess radon concentrations would then be present. The carbon columns would have to be shielded to prevent gamma exposure to the miners. The system may not work in wet mines because of moisture absorption by the carbon.

The system does appear to be technically feasible utilizing commercial carbons and standard equipment. However, additional developmental work may be necessary before such a system can be used in a mine environment. A recent study by Hopke (Ho84) has concluded that activated carbon can be used for effective cleaning of small volumes of air such as effluents from a bleeder pipe for a bulkhead.

Mine Pressurization

Positive mine pressurization has been tried several times to force the radon in the mine atmosphere back into the walls of the mine (Ko80 and Fra81). In general, these efforts have been successful in reducing the radon concentrations in the mine itself. An "air" sink is necessary to accept the radon. If the radon is forced through the ore body or surrounding area to the surface, the radon can decay before coming to the surface. If the area is impermeable, however, radon levels will return to previous levels. In tests by the Bureau of Mines (Fra81), the radon levels in the mine were reduced by 20 percent (releases to the atmosphere were not determined). The surrounding soil needs to be permeable enough to hold radon and allow for its decay, but not so permeable so as to allow significant increases in surface emissions (Ko80). The costs of mine pressurization were not available because the process was in a development stage. In a recent report, Battelle (Bl84) concluded that positive pressure ventilation has been proven ineffective in reducing atmospheric emissions of radon.

Miscellaneous Radon Control Technology

Argonne National Laboratory is experimenting with strong oxidizing agents, such as bromine trifluoride and dioxygenyl hexafluoro-antimonate, to convert the radon to another form that can be absorbed on a scrubber or absorption bed (Fra81). However, the corrosive and toxic nature of the reactants makes their use in mines impracticable and questionable. Battelle (Bl84) mentions other methods such as cryogenic methods, chemical removal, and gas centrifuge, but the costs are prohibitive. The study by Hopke (Ho84) reviewed methods for the removal of radon from uranium mine effluents. Methods, including cryogenic condensation, molecular sieves, gas centrifugation, semipermeable membranes, and hybrid systems, do not offer much promise for a practical removal system. They do suggest the exploration of the class of perfluorinated hydrocarbon compounds as possible candidate scrubbing fluids for a radon scrubbing system.

Backfilling of worked-out areas with classified mill tailings is practiced by mine operators to provide ground support in the mine (Fr81). This procedure can also reduce ventilation requirements. A study, by the Bureau of Mines and Kerr-McGee Nuclear, to determine the effectiveness of reducing radon emissions by backfilling mill tailings into the mine stopes indicated a net radon reduction of 84 percent from the stope (Frb81). This was done for only one stope in a mine. PNL (Bl84) estimated an efficiency up to 80 percent if classified mill tailings and surface sands are used for backfilling with an average cost of \$12.64 per ton of ore mined.

Increasing the height of vents is a possible method to reduce ground level radon concentrations in ambient air (Dra80). One of the conclusions based on a theoretical model was that a 20-meter release

height reduces the annual average concentration (when compared to a ground-level release) by about 60 percent at one mile from a source and by about 30 percent at ten miles from the source." An estimate of cost is \$0.493 - \$0.881/ton of ore for a 20-meter stack (Brb84). The average number of vents for a mine is about 5 (Ja80). Thus, the cost per mine would be about \$3.44 per ton of ore produced.

Vent orientation is an important factor in radon concentrations near a mine (Drc84). Because of plume rise, concentrations are much lower when vents are in a vertical configuration (rather than horizontal), resulting in a reduction factor of 80 at sites near a mine with a vertical vent configuration.

Summary of Costs and Efficiencies

A summary of the costs and efficiencies of the various radon control technologies discussed previously is shown in Table 5-3.

Table 5-3. Cost and efficiencies of radon control technologies for underground uranium mines

Method	Radon reduction (Percent)	Cost (\$/ton of ore)
Sealant coating	11 - 56	1.45 - 5.80
Bulkheading	14 - 60	0.08 - 0.34
Bulkheading with activated carbon	49 - 80	0.11 - 1.20
Mine pressurization	20	-
Stacks	60 (a)	3.44
Backfilling	80 - 84	12.64

(a) Reduction in exposure to nearby individuals.

5.4 Radionuclide Emission Measurements

Radon-222 is the radionuclide emitted from underground uranium mines which causes the greatest risk to people. The major source of radon-222 emissions to air are the mine vents through which the ventilation air is exhausted. A large underground mine will usually have several vents: some mines have as many as 14 vents. Radon-222 emissions from these vents are highly variable and depend upon many interrelated factors including: ventilation rate, ore grade, production rate, age of mine, size of active working areas, mining practices, and several other variables.

Pacific Northwest Laboratories (PNL) has measured the radon-222 emissions from 27 underground uranium mines (Table 5-4) (Ja80). The average radon-222 emission rate for these 27 mines was 5,600

Table 5-4. Measurements of radon-222 emissions from underground uranium mine vents (Ja80)

Mine	Number of vents	Measurements (Ci/y)		
		1979	1978	Average
A	4	7,400	-	7,400
B	6	4,700	4,300	4,500
C	4	5,200	3,900	4,600
D	2	3,600	-	3,600
E	14	29,800	-	29,800
F	13	9,200	9,500	9,400
G	5	2,200	1,500	1,800
H	10	15,200	-	15,200
I	11	1,700	-	1,700
J	9	7,800	8,100	7,900
K	4	7,000	5,900	6,400
L	8	1,500	1,300	1,400
R	8	15,000	14,600	14,800
T	5	1,900	-	1,900
U	3	900	-	900
V	2	1,000	-	1,000
Y	7	17,500	-	17,500
Z	3	-	2,600	2,600
AA	2	2,100	1,500	1,800
BB	5	2,100	1,800	2,000
CC	3	-	2,100	2,100
DD	2	-	1,000	1,000
EE	5	6,500	-	6,500
FF	3	2,500	-	2,500
GG	3	200	100	200
HH	2	1,000	-	1,000
II	2	500	-	500
Average	5	6,100	4,200	5,600

curies/year. The emissions from individual vents ranged from 2 to 9,000 Ci/year with an average of 1,000 Ci/year.

In addition to the mine vents, radon-222 is emitted to air from several above-ground sources at an underground uranium mining operation. These sources are the ore, subore, and waste rock storage piles. PNL

has estimated the radon-222 emissions from these sources to be about 2 to 3 percent of the emissions from the vents (Ja80). EPA has estimated the emissions from the above-ground sources to be about 10 percent of mine vent emissions (Table 5-5).

Table 5-5. Estimated annual radon-222 emissions from underground uranium mining sources (EPA83b)

Source	Average large mine ^(a) (Ci/y)
<u>Underground</u>	
Mine vent air	3,400
<u>Aboveground</u>	
Ore loading and dumping	15
Sub-ore loading and dumping	5
Waste rock loading and dumping	0
Reloading ore from stockpile	15
Ore stockpile exhalation	53
Sub-ore pile exhalation	338
Waste rock pile exhalation	3
Total	3,829

(a) Ore grade = 0.1 percent U_3O_8 . Annual production of ore and sub-ore = 2×10^5 MT, and waste rock = 2.2×10^4 MT.

The above-ground sources also emit radionuclides to air as particulates. The particulate emissions result from ore dumping and loading operations and wind erosion of storage piles. EPA has estimated that about $2E-2$ Ci/y of uranium-238 and $3E-4$ Ci/y of thorium-232 and each of their decay products would be emitted into the air at a large underground mine (EPA83b). An assessment of the health risks from these emissions showed that the risks from the particulate emissions were much smaller (a factor of 100 less) than the risks from radon-222 emissions (EPA83b). Therefore, the health risk assessment presented in the subsequent sections of this chapter will be limited to radon-222 emissions.

5.5 Reference Underground Uranium Mine

Table 5-6 describes the parameters of the reference mine which are used to estimate the radon-222 emissions to the atmosphere and the resulting health impacts. These parameters were chosen primarily from information in Tables 5-7 and 5-8. The reference mine has 5 vents in the configuration as shown in Figure 5-4.

Table 5-6. Reference underground uranium mine

Parameter	Value
Ore grade	0.22 percent U_3O_8
Ore production	112,000 tons/y
Days of operation	250 days/y
Number of vents	5
Vent height(a)	3 meters
Radon emissions	11,000 Ci/y(b)

(a) In estimating radon-222 concentrations in Table 5-9 for releases with plume rise, the following vent parameters were used: vent diameter is 1.5 meters, exit velocity is 16.2 meters/sec, and the exit temperature is 287°K (Drc84).

(b) 2,200 Ci/y from each vent.

Table 5-7. Summary of radon-222 emissions by age of underground uranium mine (Ja80)

Mine	New mines		Old mines	
	Age (years)	Radon-222 emissions (Ci/y)	Age (years)	Radon-222 emissions (Ci/y)
A	3	7,400	-	-
B	9	4,500	-	-
C	9	4,600	-	-
D	7	3,600	-	-
E	-	-	21	29,800
F	-	-	20	9,400
G	4	1,800	-	-
H	-	-	21	15,200
J	-	-	20	7,900
K	-	-	19	6,400
L	-	-	29	1,400
R	-	-	20	14,800
U	4	900	-	-
V	2	1,000	-	-
Y	6	17,500	-	-
Z	-	-	17	2,600
Average	6	5,200	21	10,900

(a) Data from measurements made in 1978 and 1979.

Table 5-8. Estimated ore production of selected mines, 1982 (Brb84)

Mine	Estimated 1982 production (10 ³ tons/y)
New Mines (Mines less than 10 years old)	
King Solomon	38.0
Velvet	51.6
Tony M	137.6
Hack Canyon	63.1
Pidgeon	(a)
Kanab North	(a)
La Sal	81.7
Hecla	14.8
Big Eagle	16.6
Golden Eagle	(a)
Mt. Taylor	328.5
Old Church Rock	28.6
Church Rock-East	72.3
Kerr-McGee	
Section 19	127.2
Nose Rock	(a)
Mariano Lake	36.8
Average	62
Old Mines (10 years or more)	
Sunday	41.7
Dermo-Snyder	58.5
Wilson-Silverbell	16.5
Lisbon	73.3
Sheep Mtn.	0
Church Rock-NE	171.9
Church Rock-1	176.8
Kerr-McGee	
Section 30-East	119.5
Section 30-West	132.4
Section 35	195.1
Section 36	111.2
Homestake	
Section 23	208.9
Section 25	67.9
Schwartzwalder	198.8
Average	112

(a) Not operational.

