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Technical Assessment of Radon-222 Control Technology for Underground Uranium Mines

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Foreword

The Office of Radiation Programs, EPA, is developing standards for radioactive air pollutants under the authority of the Clean Air Act, as amended in 1977. Technically enhanced sources of naturally occurring radioactivity, such as underground uranium mines, may release large quantities of radon-222 into the atmosphere. Because of the potential adverse health effects to population groups, underground uranium mines warrant investigation as to the feasibility of reducing the radon-222 releases. This study addresses various control options for a hypothetical mine.

In sponsoring this study, we have worked closely with the U.S. Bureau of Mines, Department of the Interior, with a common objective of protecting both the underground worker and the surrounding population by reducing the amount of radon-222 released into fresh air pathways, and hence to the environment. Readers of this report are encouraged to comment on its technical merits and conclusions. Additional information is welcome.

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ABSTRACT

This report presents the results of a preliminary evaluation of potential radon-222 control technologies for underground uranium mines. The evaluated technologies are (1) use of a 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 technology (chemical reaction of radon in contaminated mine air).

Underground uranium mines vary widely in size, shape, depth, ore grade, lithology, layout, and mining method. Accordingly, the radon sources and their emission rates also vary widely from mine to mine. A hypothetical mine was used to estimate the radon emission rates from various sources and to assess the radon control technologies. The hypothetical mine, which has the capacity of 1,000 tons of ore per day and has produced 480,000 tons of uranium ore over two years' operation, has 8.86 Ci/day radon emission into the underground mine air. This includes 4.51 Ci/day from worked-out areas and 4.35 Ci/day from working areas.

The five radon control technologies are evaluated for their application to the hypothetical mine. This includes evaluation of their effectiveness in controlling radon emission, cost, potential problems, safety considerations, and equipment availability. Sealant coating may be applied to the 2.54 Ci/day radon sources and reduce 1.01 Ci/day at a cost of $1.45 per ton of produced ore. Bulkheading of worked-out areas may be applied to the 4.51 Ci/day radon sources and divert all 4.51 Ci/day radon emission at a cost of $0.34 per ton of ore produced; 3.25 Ci/day to the exhaust ventilation system, while 1.26 Ci/day is decayed in the bulkheaded areas. (More recent information indicates that as much as 2.95 Ci/day to 3.56 Ci/day of the 4.51 Ci/day of radon from the worked-out areas may decay within the bulkheaded areas.) Activated carbon adsorption, used in conjunction with bulkheading, may be applied to 3.25 Ci/day radon sources and reduce 3.09 Ci/day, which otherwise would be discharged to the surface atmosphere, at a cost of $4.32 per ton of produced ore.

The concept of mine pressurization to reduce radon emission into the mine air appears to be promising; however, further tests are needed to verify the concept. Use of highly reactive chemical oxidants to react with radon in underground uranium mine air appears possible, but tested chemicals are very corrosive in the presence of humidity, extremely toxic, and not commercially available.

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SECTION 1

INTRODUCTION

This is the final report on the study, "Technical Assessment of Radon-222 Control Technology for Underground Uranium Mines," conducted for the Office of Radiation Programs, U. S. Environmental Protection Agency (EPA), under Contract No. 68-02-2616, Task No. 9.

The health hazards of breathing air contaminated with radon-222 and its daughter products have been recognized since the 1940's.[6] The concentration of radon daughters in the air of working areas in underground uranium mines is regulated by the Mine Safety and Health Administration (MSHA). The commonly used technique for controlling the concentration of radon daughters in the mine air is forced-air ventilation which dilutes and removes the contaminated air from the mine to the surface atmosphere. At present there is no EPA standard for the concentration of radon and its daughter products in the exhaust ventilation air from an underground mine, or the surface atmospheric air. The U. S. Nuclear Regulatory Commission (NRC) regulations for radon concentrations in air are 30 pCi/L (10 CFR 20.103) and 3 pCi/L (10 CFR 20.106) for restricted and unrestricted areas, respectively.

The Office of Radiation Programs of EPA has the responsibility for setting standards for the airborne emissions of radioactive nuclides under the Clean Air Act as amended in 1977. This includes radon-222 and its daughter products from underground uranium mines. If, in the judgement of EPA, it is not feasible to prescribe an emission standard for controlling radon, EPA may instead promulgate a design, equipment, work practice, operational standard, or a comination thereof, which is adequate to protect the public health.

Because of program requirements, EPA contracted for a two-month quick response task for a preliminary technical evaluation of the potential options for controlling radon-222 released to the surface environment from underground uranium mines based on information and literature supplied by EPA and obtained from other readily available sources.

OBJECTIVE OF THE STUDY

The purpose of this study is to provide the EPA with some of the necessary information to enable them to make a sound decision on future activities leading to the setting of emission standards or other regulations for the control of radon emissions from underground mines.

This study provides EPA with a first-cut technical assessment of various potential methods of controlling radon from underground uranium mines. The study, based on presently available literature, attempts to characterize the major sources of radon and to review promising methods of controlling radon emissions from those sources. The radon control technologies evaluated were:

- Use of a sealant coating on exposed ore surface
- Systematic bulkheading of worked out areas
- Activated carbon adsorption of radon from highly radon-contaminated air
- Mine pressurization to suppress radon emission
- Use of chemical oxidants to react with radon.

This study is solely aimed at means of preventing radon release to the surface atmosphere. It considers only active underground uranium mines and does not consider completed or inactive mines. This study also does not address open pit mining, subsequent milling and tailings, atmospheric diffusion, the ultimate health effect of diffused radon, or the question of mine workers' protection, except where such means of preventing radon release impinges upon the subject.

PROJECT METHODOLOGY

To fulfill the objectives of this technical assessment, four major tasks were performed:

- Characterization of radon source
- Definition of a typical mine, "the case mine"
- Conceptual design of radon control systems
- Technical and cost evaluation of control systems.

Characterization of Radon Sources

The available literature pertaining to the problem, sources, and emission rate of radon in underground uranium mines, was reviewed. Technical experts in the field were also contacted for consultation[1]. It became apparent that information on the radon sources is limited, and that radon emission is a very complex subject which depends on many variables such as the ore characteristics, mining method, climate, and age of mine.

Since this study is a preliminary assessment, it was decided to use a simplified version of the radon source which would allow a generalized assessment of the problem. A discussion of the radon problem and a simplified source is presented in Section 3.

Definition of Case Mine

The assessment of radon control technology required a representative underground uranium mine to be used as a model mine (the Case Mine). However, it was quickly realized that all underground uranium mines are different in their size, shape, mining methods, or radon emission. It was not possible to define a typical underground uranium mine. It was decided, with EPA approval, that a simple underground uranium mine of 1,000 tons per day using the modified room-and-pillar mining method would be hypothesized for the purpose of this study. The case mine and its radon source are presented in Section 4.

Conceptual Design of Radon Control Systems

Conceptual design of the radon control systems applied to the case mine was necessary for the assessment of these technologies. Available literature on these technologies was reviewed to develop design criteria. There is very little actual experience of these technologies, except for the limited practice of bulkheading and limited test of sealant coating. Each control technology was applied in a manner that was effective for the hypothetical case mine. The conceptual design is presented in Section 5.

Technical and Cost Evaluation

Each control system applied to the case mine was evaluated for:

- Effectiveness in radon control
- Capital and operating costs
- Potential problems
- Assessment of operational requirements
- Design and safety consideration

- Availability of material and equipment.

The cost is an approximation based on the conceptual design of the radon control systems applied to the case mine. An estimating method consistent with the conceptual nature of the design was employed for this study. All cost data represent 1978 dollars.

The technical evaluation is based on the application of these technologies to the case mine. Wherever possible, the application to real mines is also discussed. The technical and cost evaluation is presented in Section 5.

SECTION 2

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The results of this study are summarized in this section. Conclusions and recommendations for future EPA efforts in controlling radon release to the surface environment are also included.

RADON SOURCE IN UNDERGROUND URANIUM MINES

The radon source and radon emission rate in underground uranium mines varies considerably depending on the geological characteristics of the ore deposit, ore grade, mining technique, and mine atmosphere. Areas specially noted for radon emission in underground uranium mines are:

- Surface of drifts driven through the ore body
- Exposed surface in extracted area
- Raises or drifts near the ore body
- Muck piles in working areas
- Ore spills and ore cars in the haulage ways
- Ground water entering mine workings after passing a uranium deposit.

Radon emission rate from an exposed mine surface varies in a range of 10 to 100 pCi/ft^2-sec depending on the ore grade, mine environment, rock characteristics, and mining activity. For this study, the following approximate emission rates are assumed:

- 55 pCi/ft^2-sec (4.8×10^{-6} Ci/ft^2-day) for a medium grade ore surface (1)
- 28 pCi/ft^2-sec (2.4×10^{-6} Ci/ft^2-day) for a low grade ore area*
- 2.4×10^{-3} Ci/ton-day for ore muck piles.

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*This is in good agreement with a more recent value of 22.4 pCi/ft^2-sec calculated from information in reference 33.

Groundwater entering a mine working after passing through a uranium deposit, may be one of the major radon sources. However, it is not possible to estimate, based on presently available information, the rate of radon emission from the mine water into the mine air. This study did not include the mine water as a source of radon emission into the mine air.

UNDERGROUND URANIUM MINES AND CASE MINE

Because uranium ore deposits are erratic in size, shape, and lithology, every mine has a different layout and a different mining method. Defining a typical underground uranium mine was not possible. For this study, a hypothetical mine, defined only by major radon sources, is selected and used for evaluation of the radon control technology.

The Case Mine

The Case Mine has a large uniform tabular ore body which is mined by modified room-and-pillar stoping method. The case mine has:

- Eight developing stopes at various stages of development (250 TPD ore from eight developing stopes)
- Two developed stopes ready for extraction
- Five extracting stopes at various stages of extraction (750 TPD ore from five extracting stopes)
- Twenty-five completed stopes
- A total of 240,000 tons per year from 12.5 stopes per year
- Each completed stope has 77,000 ft^2 of exposed surface and 300,000 ft^3 of air space
- Ventilation rate of 240,000 CFM.

The Radon Emission Rates in the Case Mine

In the case mine, 51 percent of the radon is emitted from 25 extracted stopes (mined out area), while the remaining 49 percent is emitted from active working areas (see Table 2). Not all of the radon emitted into the underground mine space is discharged to the surface environment. Some of the radon, especially that emitted into an isolated space such as a bulkheaded mined out stope, will be trapped and subsequently decayed.

Radon sources and emission rates in the case mine are summarized as follows:

Radon Sources	Emission Rate Ci/day
8 Developing Stopes	
Drifts	1.43
Muck piles	0.38
2 Developed Stopes	
Drifts	0.71
5 Extracting Stopes	
Drifts & extracted areas	1.35
Muck piles	0.48
25 Extracted Stopes	
Extracted areas	4.51
	8.86

ASSESSMENT OF RADON CONTROL TECHNOLOGIES

Five radon control technologies are applied to the Case Mine and evaluated for their cost, effectiveness, operational requirements, and potential problems. An assessment of radon control technologies is summarized in Table 1.

Use of Sealant Coating

In the Case Mine, only drifts of developing stopes are coated. Annually, 530,000 ft^2 of drifts are coated using 2,400 cubic yards of Shotcrete, 69,600 gal of HydroEpoxy 156, and 17,000 gal of HydroEpoxy 300, at a total cost of $344,300 (see Section 5 for details). The cost per ton of ore is $1.45. The sealant coating reduces radon emission from drifts of the developing stopes by 1.01 Ci/day; 11 percent reduction of the total radon source.

Bulkheading of Extracted Stopes

Every extracted stope in the case mine is sealed using eight bulkheads as soon as it is completed. All of the bulkheaded stopes are connected to the exhaust ventilation system using bleeder pipes. The systematic bulkheading of the 12.5 stopes per year, with 100 CFM* bleeding from each stope, will divert all 2.25 Ci/day radon source in 12.5 completed stopes and discharge 1.62 Ci/day to the surface. The bulkheading cost of 12.5 worked-out stopes is $80,000 per year ($0.34 per ton of ore).

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*More recent information indicates that flow rates of 10-20 CFM are sufficient to maintain the bulkheads at negative pressure[32].

TABLE 1. ASSESSMENT OF RADON CONTROL TECHNOLOGIES SUMMARY

	Applicability		Radon Reduction		Cost
	Ci/Day	% of Total(1)	Ci/Day	% of Total(1)	$/Ton of Ore
Sealant Coating	2.54	29	1.01	11	1.45
Bulkheading	4.51	51	1.26(2) (4.51)	14 (51)	0.34
Activated Carbon	3.25(2)	37	3.09	35	4.32
Mine Pressurization(3)	--	--	--	--	--
Miscellaneous Technology(3) (Use of chemical oxidants)	--	--	--	--	--

NOTES: (1) Based on 8.86 Ci/day radon emission from the case mine.

(2) Diversion of 4.51 Ci/day from 25 worked out stopes, 1.26 Ci/day decay in bulkheaded worked out stopes, and emission of 3.25 Ci/day into the exhaust ventilation system.

(3) Available information was not enough to evaluate the effectiveness and cost.

Activated Carbon Adsorption of Radon from Contaminated Mine Air

The systematic bulkheading of all extracted stopes with 100 CFM bleeding from each stope, diverts all radon emitted in the extracted stope (0.18 Ci/day for each stope) from the mine air, but discharges 72 percent of it (0.13 Ci/day) to the exhaust ventilation system and eventually to the surface environment. The difference (0.05 Ci/day) decays in the bulkheaded stope.

In the case mine application of the activated carbon system, one carbon system is provided to each bleeder pipe of the bulkheaded stopes. The carbon systems remove 95 percent of the radon from the bleeder pipes, which otherwise will be discharged to the exhaust ventilation air.

Based on five years average life of the carbon systems, each system costs $83,000 to install and operate for five years; this represents $4.32 per ton of ore. Applied to all 25 bulkheaded stopes in the case mine, the carbon systems will remove 35 percent (3.1 Ci/day) of the radon emitted from the entire mine at the capital cost of $825,000 and an annual operating cost of $250,000 (amortization is not included).

Mine Pressurization

Mine pressurization has been found to be effective in some cases in controlling radon emissions into the mine atmosphere. However, its effectiveness in controlling radon emissions into the surface environment, which is the primary concern of this study, has not been proven.

Effectiveness of mine pressurization in reducing the radon emission rate depends on the flow of gas (gas in the interstitial pores and mine air) from the exposed ore surface into the ore body, caused by the positive pressure (the mine pressure is higher than the surface atmospheric pressure). However, the gas flow has to be slow enough to allow radon in the gas to decay before reaching the ultimate sink — the surface environment. Further tests are required to confirm the effectiveness of mine pressurization.

A mine could be pressurized using readily available equipment. The cost for mine pressurization, which would vary widely for different mines, is not determined in this study.

Miscellaneous Radon Control Technology (Use of Chemical Oxidants)

The concept of removing radon from a contaminated uranium mine air by reacting it with liquid and solid chemical agents, does not appear feasible at this time. Tested chemicals are extremely corrosive in the presence of moisture, toxic, and not commercially available. Use of these chemicals in an underground uranium mine would be difficult because of their toxic nature and hazardous by-products.

CONCLUSIONS AND RECOMMENDATIONS

An underground uranium mine of 1,000 tons per day has radon sources emitting approximately 9 Ci/day. If all radon emitted into the mine air is discharged to the surface atmosphere via the exhaust ventilation air, this would represent a discharge of 240,000 CFM of the exhaust ventilation air having 920 pCi/L. Whether the radon emission of 9 Ci/day from an underground uranium mine represents a public health hazard is not known at this time. Presently, there is no EPA ambient air quality standard or emission standard for radon concentration. The NRC regulation for radon concentration in unrestricted areas is 3 pCi/L (10 CFR 20.106). The hazardous exposure limit and atmospheric dispersion of radon must be determined before concluding whether or not the radon emission from underground uranium mines is a public health hazard.

Limited reduction of the radon emission is possible using currently available technology. Sealant coating applied to the case mine reduces 11 percent of the total radon emission at the cost of $1.45 per ton of ore. Bulkheading of extracted stopes is cheap ($0.34 per ton of ore) and very effective in preventing radon contamination of the mine air (diverts 51 percent of the total radon emission), but less effective in reducing the radon emission to the surface environment (reduces 15 percent* of the total radon emission by decay). Activated carbon system applied to bleeder pipes of the bulkheaded stopes is more effective (removes 35 percent of the total radon emission), but also more expensive ($4.32 per ton of ore).

Mine pressurization may be effective for reducing the radon emission into the mine air and into the surface environment, but further tests are required to verify the concept. Removal of radon from the contaminated air by reacting with chemicals appears impractical at the present time because of the toxicity of chemicals and by-products.

This study is based on limited information. If EPA decides that radon discharge on the order of 10 Ci/day from an underground uranium mine represents a public health hazard, then the further studies listed below will assist EPA by providing additional information on the characterization of radon sources and the applicability of control technology. Further studies may include:

- Characterization of the radon source

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*Flow rates of 10/20 CFM would result in reductions of 40/33 percent of the total radon emission to the surface environment (see page 33).

- Classification of underground uranium mines into groups which have similar radon sources and may also have similar radon control strategies
- Development of inexpensive sealant materials that are effective in an operating mine environment
- Development of better bulkhead
- Test of mine pressurization
- Development of effective activated carbon system.

Characterization of Radon Sources--Better radon emission rates for various sources are required for a meaningful assessment of the radon problem and control requirement. A source characterization study should be conducted to develop a list of radon sources and radon emission rates as a function of the mineral property, mining technique, and mine environment.

Classification of Underground Uranium Mines--Radon emission rates and applicable radon control technology vary from mine to mine. Grouping of the uranium mines into those which have similar radon sources and which would probably utilize similar radon control strategies is necessary in order for EPA to promulgate a fair standard, if one is required.

Development of Inexpensive Sealant Material--The cost of the sealant coating in this study is primarily that of the material cost. It is very high compared to an asphalt emulsion sealant tested on uranium tailings. Finding a cheaper and effective coating material is essential if there is to be wide coating application.

Development of Better Bulkhead--Bulkheads commonly used by the present uranium mines are found to be ineffective in forming an airtight seal. Development of a better bulkhead that is more durable and airtight is necessary.

Test of Mine Pressurization--The concept of mine pressurization to reduce radon emission into the atmosphere of underground uranium mines is attractive. However, further tests are required to confirm the effectiveness of a long-term mine pressurization in reducing the radon emission and to determine its impact on the mining activity as well as the surface environment.

Development of Effective Activated Carbon System--The activated carbon systems suggested in this study require a series of field tests to debug the components and to optimize the overall systems. Actual demonstration of the activated carbon application is essential if the industry is to accept the technology.

SECTION 3

RADON SOURCES AND EMISSION RATES IN UNDERGROUND URANIUM MINES

All rocks, sands, and soils containing uranium also contain some radium. Except for places where chemical leaching has resulted in depletion of uranium or radium, the two will be found in radioactive secular equilibrium.

Radium-226 decays to radon-222, which further decays to a series of daughter products. The radium decay products and their half-life are as follows:

Element	Half-Life	Radiation (Mev)
Radium-226	1,620 y	α-4.7, γ-0.19
Radon-222	3.82 d	α-5.48, γ-0.51
Polonium-218	3.05 m	α-6.00
Lead-214	26.8 m	β-0.65, γ-0.29
Bismuth-214	19.7 m	β-1.5, γ-1.8
Polonium-214	1.6×10^{-4} s	α-7.68
Lead-210	22 y	β-0.02, γ-0.05
Bismuth-210	5.0 d	β-1.16
Polonium-210	138 d	α-5.3, γ-0.80
Lead-206	Stable	

When radium decays in an ore body, it produces radon. Radon is a gaseous and not too chemically reactive element. Radon will diffuse through the ore body. If radon diffuses out of the ore body into the mine atmosphere before it decays, then radon and its decay products will become airborne radioactivity. Radon has a half-life of 3.82 days. If radon decays within the ore body or host rock, its chemically reactive decay products, which are solids, will be permanently trapped in the ore body.

Uranium mining activity exposes new radium containing ore surfaces to the mine atmosphere. The mining activity not only increases new ore surface (new radon sources), but also reduces the distance for radon to diffuse through before entering the mine atmosphere. When uranium ore is broken, trapped radon will escape into the mine atmosphere; then the radon emission will reach an equilibrium determined by the ore characteristics and the mine atmospheric condition. Because of the long half-life of radium (1,620 years), the radon emission from the exposed ore surface will continue a long time.

The rate of radon production within an ore body is independent of the mine atmospheric conditions or mining activity. The radon production rate depends only on the radium concentration and is nearly constant throughout the mine life. However, the amount of radon that gets into the interstitial pore space and diffuses through the ore body into the mine atmosphere depends on the ore characteristics (porosity, ore fracture, and ore thickness), moisture content, groundwater flow, and the mine atmospheric conditions (temperature, pressure, and humidity).

Generally, an increase in the mine atmospheric pressure decreases radon emission; that is, high atmospheric pressure creates a pressure gradient which causes flow of mine air through the pores away from the exposed surface into the ore body, thereby suppressing diffusion of radon into the mine atmosphere. However, the extent of this effect is greatly dependent on the porosity of the ore body and host rock. There has to be an area of sustained low pressure in order to maintain a continuous flow. There have been a number of theoretical and experimental investigations [2, 3, 4] on the subject. The effect of pressure on radon emission is discussed in a later section on mine pressurization.

Diffusion of radon through the ore body is expected to increase as the mine temperature increases, as the gas diffusion coefficient increases with the temperature. However, temperature variation in an underground uranium mine is generally in the narrow range of 15 - 30°C and the effect of temperature variation on the radon emission rate is not expected to be significant.

Moisture of mine air and of the ore body appears to have a considerable effect on the radon emission[5]. The radon emission rate is low at very low moisture, but increases rapidly with increasing moisture, quickly reaching a plateau. The moisture of normal mine air is usually high enough that the plateau rate is reached. Mechanism of the moisture effect is not well understood. It is cited[5] that the moisture effect is a surface absorption phenomenon; that is, the dry mineral grains may absorb radon thus preventing its movement out into the mine atmosphere. When the mine atmosphere contains high moisture, the mineral grains are saturated with water molecules, and radon moves through the media without being absorbed. When the ore becomes supersaturated, radon has to diffuse through the water in the pore and the radon emission is decreased. As much as 60 percent difference in the radon emission between a dry and wet ore has been reported [5].

Mining activity, especially blasting, also affects the radon emission. However, this is a momentary increase and the peak usually disappears quickly.

Thus, the rate of radon emission from an exposed uranium ore body varies widely with such variables as radium concentration in the ore, ore porosity, mine temperature, mine pressure, mine humidity, mining activity, etc. It also depends on the nature of the exposed surface; size and shape of broken pieces, and roughness.

Areas of major radon emission in an underground uranium mine are:

- Stope development areas where ore bodies are initially exposed by drifting
- Stope extraction areas where ore is extracted. These areas have exposed ore surfaces and muck piles which have a high surface area per ton of ore.
- Completed stope areas where ore has been extracted and ribs and backs are caved in, exposing low grade ore (waste ore)
- Raises driven to the ore body from haulageways. As these raises are driven into the ore body, they expose ores.
- Haulageways where broken ores are transferred from an active stope area to the shaft area. Generally, a haulageway is located beneath the ore and itself is not a radon source, but ore is moved through the haulageway and ore spills will emit radon.
- Areas where mined ores are stored temporarily. In continuous mining operation, mined ores are frequently stored in drifts and ore passes.
- Drain ditches carrying mine water which was in contact with the ore body may release radon.

It is impossible to accurately predict the radon emission rate from a given exposed ore surface, or to accurately estimate the exposed area. As a rule of thumb, an emission rate of 55 pCi per square foot of exposed surface per sec has been suggested for a medium grade uranium ore[1]. Neither the quantity of mine water per ton of ore nor the radon emitted from it can be determined at this time. In the estimation of radon emission rates in the case mine, mine water was not included.

It has been reported[5] that approximately 4 to 9 square feet of the ore surface is exposed for each ton of ore mined; the higher figures for a small mine. Assuming an average figure of 7 square feet of the exposed surface per ton of ore mined, a uranium mine of 1,000 tons per day, operating 240 days per year, will create 1.68 million square feet of new exposed ore surface annually, and new radon sources of 8 Ci/day every year of the mine operation.

Not all of the radon emitted into the mine air is taken out of the mine into the surface atmosphere. Some of the worked out stopes are bulkheaded or backfilled. Some of the worked out stopes being used as airways are partially blocked using bulkheads to isolate parts of the worked out area and reduce the radon contamination. Radon emitted into these isolated spaces is trapped until it either decays or leaks out into the mine atmosphere.

HEALTH HAZARDS OF UNDERGROUND URANIUM MINE AIR

The health hazards of breathing uranium mine air contaminated with radon-222 and its daughter products have been recognized as early as the 1940's[6]. The concentration of each daughter product depends on the time that has elapsed after the radon contamination (age of the air). In general, the mine atmosphere contains only the first five daughter products:

Element	Half-Life	Radiation (Mev)
Radon-222	3.82 d	α-5.48, γ-0.51
Polonium-218 (RaA)*	3.05 m	α-6.00
Lead-214 (RaB)*	26.8 m	β-0.65, γ-0.29
Bismuth-214 (RaC)*	19.7 m	β-1.5, γ-1.8
Polonium-214 (RaC')*	1.6×10^{-4} s	α-7.68
Lead-210 (RaD)	22 y	β-0.02, γ-0.05

* Health Hazard Elements

When mine air contaiminated by radon and its daughters is breathed into the lungs, radon, being an inert gaseous element, is not retained in the lungs. However, the daughter products, which are highly ionized and attached to airborne dust particles, may be retained in the lungs.

In terms of health hazards, the alpha emitting daughter products, polonium-218 and polonium-214 (Radium A and Radium C'), are of major concern. However, lead-214 and bismuth-214 are also included as hazardous isotopes because they may also be retained by the lung tissue during respiration and later decay to alpha emitting polonium-214. The beta and gamma rays emitted by lead-214 and bismuth-214 make negligible contributions to the radiation dose in the lung tissue. Because of the long half-life of lead-210, it is not expected to remain in the lungs and is excluded from the dose calculation.

Because of the extremely short half life (0.00016 sec) of polonium-214 (RaC'), bismuth-214 (RaC) and polonium-214 (RaC') are considered as a single isotope emitting alpha, beta, and gamma radiation with the half-life (19.7 min) of bismuth-214 (RaC).

Each atom of polonium-218 (RaA) retained by the lung tissue produces 13.68 Mev of alpha energy (6 Mev from polonium-218 and 7.68 Mev from polonium-214). Each atom of lead-214, bismuth-214, and polonium-214 produces 7.68 Mev. The radiation intensity associated with an underground uranium mine is measured by a unit called "Working Level" (WL) [7].

> "One WL is defined as any combination of first four radon daughters — RaA, RaB, RaC, and RaC' — in one liter of air which ultimately produce 1.3×10^5 Mev of alpha energy."

When radon enters uncontaminated mine air, the air has initially zero daughter products and zero WL. Radon itself is not included in the radioactivity included in the WL. As radon decays, it produces the daughter products and the daughter products contribute to the WL. Starting with 100 picocuries of radon (3.7 disintegration per sec., or 6.5×10^{-16} gram), build-up of the total WL and each daughter's contribution to the WL as a function of the decay time is shown in Figure 1.

As seen in Figure 1, the health hazards (alpha radiation dose) of mine air depends not only on the radon radioactivity, but also on the age of the mine air. Increased ventilation rate in a given mine reduces the health hazard (working level) first by diluting the contaminated air, and secondly by shortening of the air retention time in the mine, hence, resulting in a "younger" air. However, a high ventilation rate does not reduce the total radon and its daughter products emitted into the surface environment. A high ventilation rate will probably result in increased radon and daughter discharge into the surface environment by not allowing radon to decay in the mine.

Presently, the Federal Regulation, administered by MSHA of the Department of Labor, limits the radon daughter concentration in the mine air in the underground working area to 1.0 WL and a total annual exposure of 4.0 Work Level Month (WLM). One WLM is defined as 173 hours exposure to a radon daughter concentration of 1.0 WL.

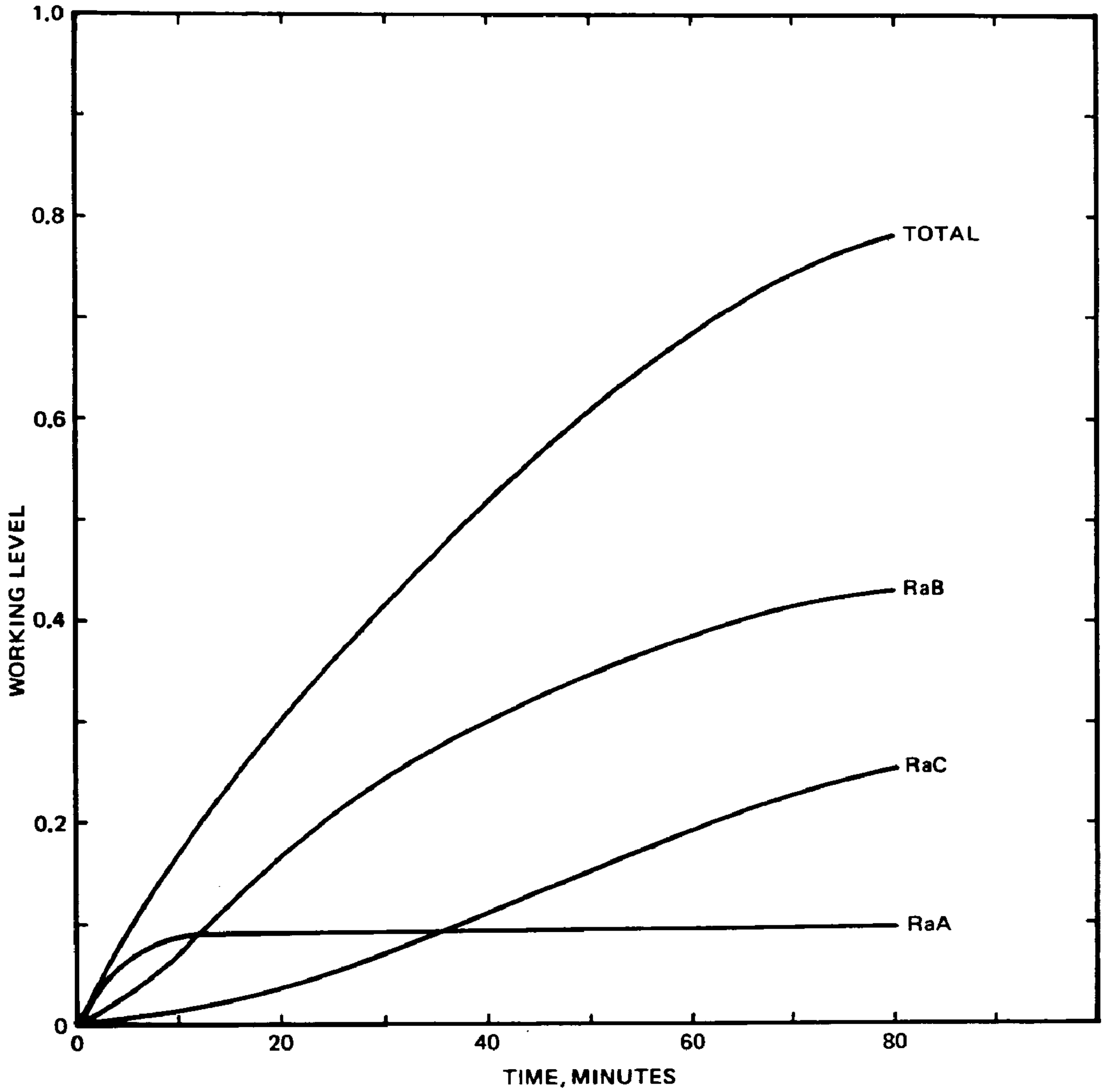

Figure 1. Growth of working level (WL) in pure radon (100 pCi/L)

It should be recognized that the working level is a measurement for mine worker exposure to alpha emitting particulates, and not a true measure of the total air contamination. For the general public safety, radon in the surface ambient air should be included because radon will eventually decay and produce hazardous daughter products. The working level does not include potential exposure of gamma radiation from radon daughter products trapped inside the exposed ore body. The gamma radiation from the trapped radon daughter products may be a significant source of radiation exposure; however, quantitative information on the gamma source is not available at this time. The gamma radiation source is not included in this study.

SECTION 4

UNDERGROUND URANIUM MINES AND THE CASE MINE

The majority of uranium deposits in the United States are in New Mexico, Wyoming, Colorado, Utah, and Texas. Nearly 90 percent of the uranium deposits in the United States are sandstone deposits. Ore deposits are generally tabular layers that lie nearly parallel to the bedding planes. The flat-lying deposits usually occur in more than one stratigraphic horizon and they may occur in clusters. Ore bodies are generally irregular in shape and size, ranging from small masses of only a few feet in width and length to those that are tens of feet thick, hundreds of feet wide, and thousands of feet long. Ore bodies range from a few hundred to several million tons.

Presently, open pit, in-situ leaching, and underground mining techniques are used for uranium mining. However, future uranium production is expected to be more from underground mining.

Because of the extreme variation of uranium ore bodies in size, shape, depth, continuity, physical properties, geologic structure, grade, and groundwater condition, each underground uranium mine is unique in its layout and mining method. Each mine is a one-of-a-kind. Furthermore, the configuration of a specific underground uranium mine changes continuously as operation progresses. Defining a typical underground uranium is impossible.

Some general features of underground uranium mines are discussed here by following sequential activities from shaft sinking to ore production. Later in this section, the hypothetical underground mine used in this study is defined. This hypothetical mine (the case mine) is defined solely for the purpose of identifying the major radon sources and evaluating the radon control technologies applied to these radon sources.

GENERAL FEATURES OF UNDERGROUND URANIUM MINES

A schematic section of a hypothetical underground uranium mine is shown in Figure 2. The sequential events in development of such a mine would be as follows:

- Product shaft sinking

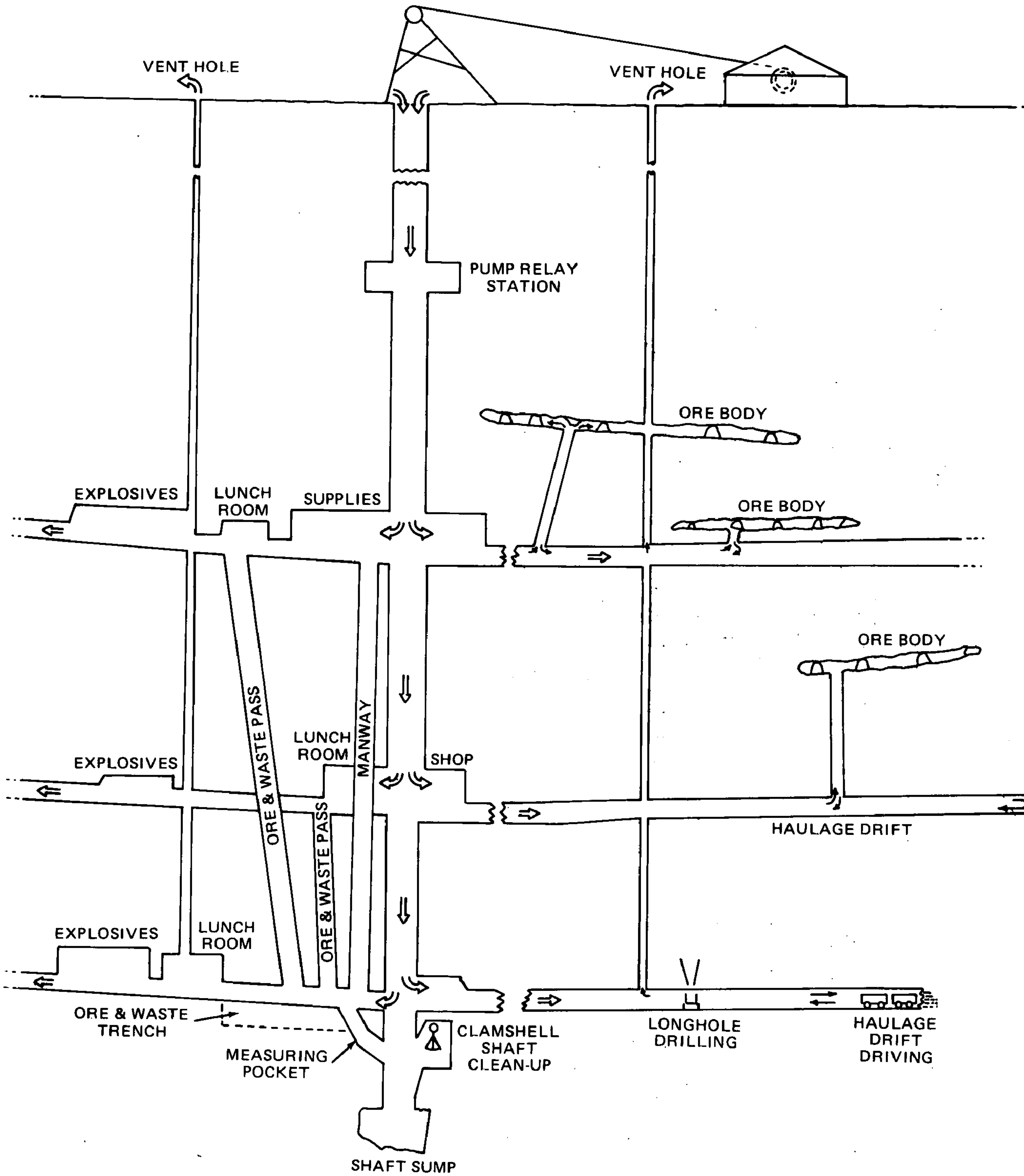

Figure 2. Schematic diagram of an example underground uranium mine.

- Haulage drifting
- Ventilation shaft sinking
- Longhole exploration
- Raising to stope level
- Stope development (primary ore production)
- Stope extraction (final ore production).

Production Shaft

Depending on depth and geologic conditions, either vertical or inclined shafts may be used as access to the ore. However, the trend is toward vertical shafts as deeper deposits are developed. These range in depth from a few hundred feet to the present-day maximum of about 3,000 feet currently being established in New Mexico.

Modern production shafts are circular and concrete lined, with internal diameters ranging from 10 to 16 feet depending on production requirements. Ore and waste ore are hoisted in two skips operating in balance. Utility lines (electric cables, water and compressed air pipes) are attached to the shaft wall.

The production shaft will generally extend a hundred feet or more below the production level in order to accommodate spillage clean-up and sump capacity. It is generally located outside the ore perimeter and does not, therefore, present a radon problem.

Haulage Drifts

Following shaft construction, haulage drifts are extended out below the anticipated ore horizons. They will usually be driven about 8 feet by 9 feet, with a 1 percent gradient to favor both the loaded haulage and mine drainage.

Since the haulage drifts are driven below the ore horizon in barren or near barren material, they should not pose a radon problem in themselves. However, unexpected extension to the ore body and isolated ore masses may occasionally be encountered.

Groundwater seeping into the haulage drift system is confined to a shallow ditch established to one side of the drift. In some instances, such groundwater may have passed through a high radon area and may, consequently, contain dissolved radon. This would then be released into the haulage drift.

Longhole Exploration

Following haulage drift development, a series of exploratory longholes are drilled upward and outward from the haulage to better delineate the ore bodies in respect to thickness, grade, elevation, and dip or roll. The drilling is normally done in a fan-shaped pattern. The angle, depth, and number of holes per fan may vary. Hole diameter is generally 1-3/4 inches, and they may serve to drain water from the ore horizon prior to mining. They will most likely become plugged during the actual mining process.

Raisings to Stope Level

Raises are openings established between the haulage and ore horizons to provide access for men, materials, fresh air, broken ore, and exhaust air. A stope (a unit working area) will have two or more raises. They are generally about 4 feet in diameter and steel lined. They are usually not considered to be major radon sources.

Stope Development and Extraction

In planning for the extraction of an ore deposit, the ore bodies are divided into suitably sized blocks that can be mined conveniently as working units. These are known as stopes. The size and shape of a stope may vary, depending on the ore body geometry, its dimensions, and the mining method.

The ore in a stope is usually removed in two stages; stope development stage and stope extraction stage. The stope development stage comprises development of a drift network within the ore body to provide access to all portions of it. As much as 30 to 35 percent of the total ore may be removed in this development stage. The stope extraction stage consists of removal of all remaining mineable ore.

The stoping method varies widely from mine to mine, and even place to place within the same mine. It depends on the ore body geometry and geology, the distribution of ore, the nature of the ground, and the presence of water.

A commonly used stoping method for relatively thin, flat-lying ore bodies is that known as "modified room-and-pillar". It provides excellent opportunity for close extraction of a deposit and for mining to the full extent of the ore. At the same time, low grade ore or barren material may be left behind in the worked out areas. Other stoping methods such as sub-level open stoping or cut-and-fill stoping are also used for mining thick and massive ore bodies or very unstable ore bodies. These methods offer less flexibility and less opportunity for effective ore extraction and ore quality control.

A mine based on the modified room-and-pillar method is selected for this study. There are numerous variations of the modified room-and-pillar stoping method practiced in uranium mining. For the purpose of identifying potential radon sources and their control methods, a simplified version of a modified room-and-pillar stoping method is presented here.

Modified Room-and-Pillar--The modified room-and-pillar stoping method is a typical method for a competent ore body of 15 feet or less thickness. It is the most commonly used. In the modified room-and-pillar stoping method, a network of development drifts produces a series of pillars to be mined during the stope extraction stage. Normally, the drifts are 6 feet by 6 feet and the pillars are 40 feet by 40 feet (Figure 3).

Once the drift network is completed, the stope is ready for extraction. However, a developed stope may not be extracted for as much as six months or even a year. The stope development is also a sort of exploration activity, and often is handled by a separate crew from the stope extraction. During the stope development, and before the extraction starts, the exposed surfaces of the drifts and ore muck piles are the primary radon sources. Some drifts will be left intact longer than others, depending on the mining plan and schedule.

During the stope extraction, pillars are blasted and removed through drifts to raises using slushers or loaders. The extraction generally begins away from the ore pass and progresses toward the ore pass. Some pillars of low grade ore may be left behind in order to control subsidence. During the stope extraction, ore muck is piled in the stope and is the major radon source. In addition, the exposed surface of low grade mineralized rock left behind and ore pillars which have not been removed also emit radon.

When the extraction is completed, most of the pillars are gone and the open cavity begins to cave in. Some of the drifts may have been left intact because of poor quality ore, for future access, or for other reasons. The exposed surfaces of the mined area (mineralized rock) and of the unmined drifts will continue to emit radon and contaminate the air in the mined stope. Unless the air in the extracted stope is effectively isolated and confined, it may leak into and contaminate ventilation air.

Ventilation System

Adequate ventilation is needed in all underground mining to supply fresh air to the mine workers and to flush out air contaminated with dust and fumes. In underground uranium mining, the need for adequate ventilation is even more acute because of the need to dilute and remove mine air contaminated with radon and its daughter products. Because each underground uranium

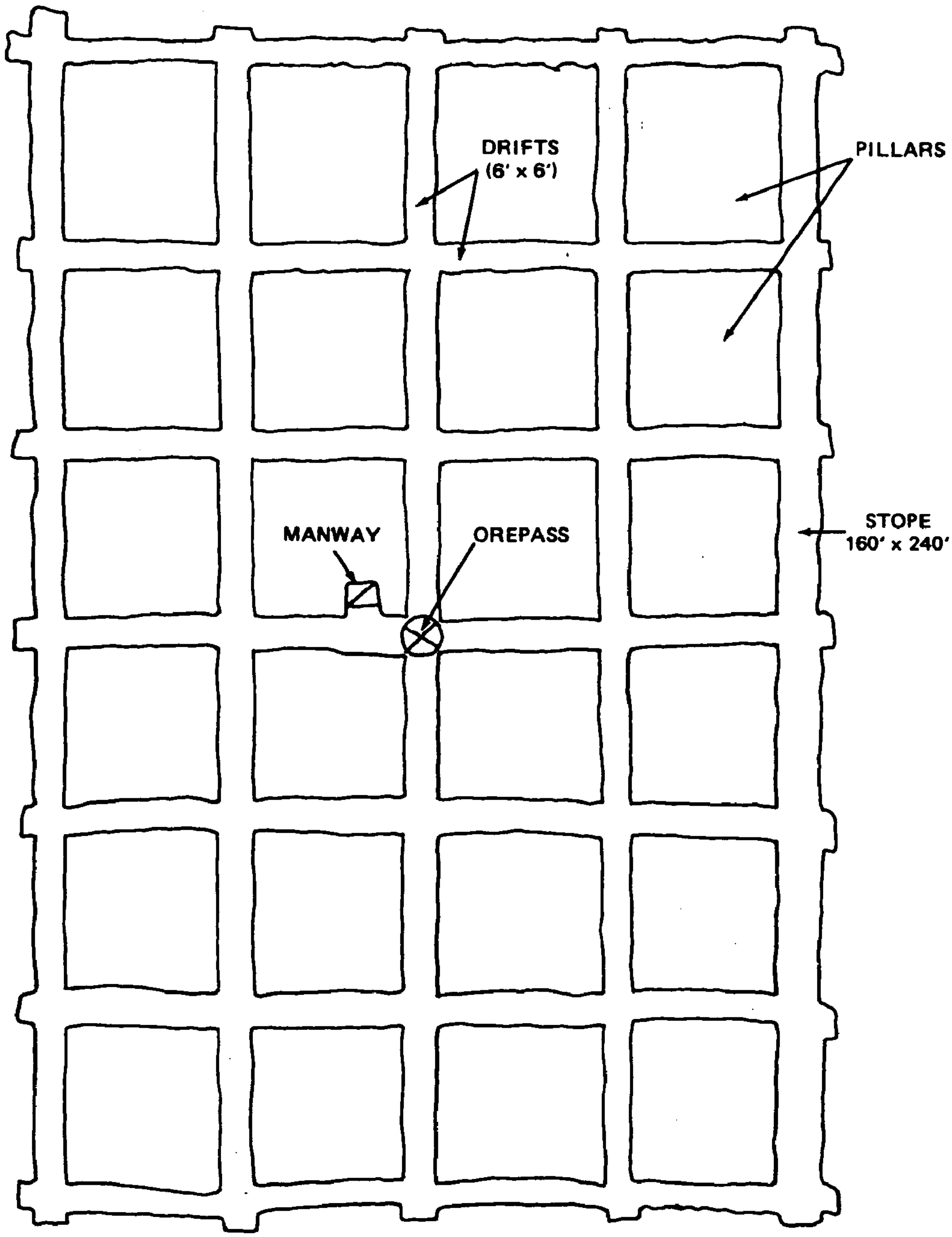

Figure 3. Modified room-and-pillar stope.

mine has a one-of-a-kind layout and mining plan, the ventilation system is also unique for each.

The ventilation system usually consists of a primary and several secondary systems. The primary ventilation system includes the main intake airway, fresh airways, exhaust air drifts, and exhaust ventilation shaft. Fans are used on either the intake shaft or exhaust shaft. Positive pressure ventilation in the primary system results from the use of downcast fans at the ground surface and negative pressure from the use of upcast exhaust fans. The production shaft and haulage drifts are commonly used as fresh air intake and fresh airways. In a large mine, there may be more than one shaft for fresh air intake and a combination of downcast and upcast fans at different vent shafts.

The secondary system, sometimes called "booster" or "auxiliary" system, consists of fans and vent tubing to redirect portions of the primary air supply to specific working areas that are not on the main ventilation system. These systems utilize small fans (5 - 25 HP) which usually push air through flexible tubing (bags) to working areas.

In a modern mine, exhaust air from working areas contaminated with radon is collected into exhaust drifts and routed directly to the exhaust shaft. However, in older mines, radon contaminated air from a working area is often discharged into the next working area or into the primary air system, thereby contaminating it. In older mines operating under positive ventilation, exhaust air is usually allowed to escape by a convenient route — which might be the main access shaft. Modern practice of underground uranium mining, however, dictates that radon contaminated exhaust air be conducted away through segregated exhaust drifts other than haulage drifts and shafts. More and more mines are taking great care to separate exhaust airways and taking steps to prevent exhaust air from contaminating the fresh air supply.

As a rule of thumb, one cubic foot per minute of fresh air per annual ton of ore removed from the mine has been suggested[8]. An underground uranium mine with 1,000 tons per day capacity (240,000 tons per year) will require 240,000 CFM ventilation. The ventilation system is discussed further in a later section on mine pressurization.

THE CASE MINE

Assessment of radon control technologies for underground uranium mines requires the definition of a typical underground uranium mine. The source and quantity of radon have to be defined to determine the feasibility and effectiveness of the radon control technologies.

However, because of the erratic nature of uranium ore deposits, each mine has a unique layout, mining plan, and mining method, each different from other mines. The characteristics of the radon source and the radon emission rates in one mine are also different from another. The application of radon control technology has to consider each mine separately. The time and manpower limits of this study do not allow for the study of many mines, or the details of any one mine.

The radon control technologies evaluated in this study are still in an early development phase. There are uncertainties in their applicability and effectiveness. Additional development work is required before these technologies become ready for an actual application.

For the purpose of this study, simplification of the usually complex underground uranium mine was necessary. A 1,000 tons per day mine of an ideally uniform ore body was selected for the study. The selected mine (the case mine) is based on one mining method — modified room-and-pillar stoping. All stopes are the same size and height.

The radon emission rates from various radon sources are approximated based on uniform emission rates for the drift surfaces in the ore (55 pCi/ft^2-sec), surfaces of waste ore (28 pCi/ft^2-sec), and ore muck piles (2.4×10^{-3} Ci/ton-day).

In view of this study being a preliminary evaluation of the technologies yet to be developed, the simplification of the mine and the approximation of the radon emission rates were necessary and appear justified. The radon sources and emission rates of the selected mine are summarized in Table 2.

The design and operating conditions of the case mine are summarized as follows:

	Case Mine
Ore Deposit:	Medium grade, large flat ore body of uniform 10 feet mineable ore thickness.
Mining Method:	Modified room-and-pillars, haulageways under the ore body. Drifts in the ore body are 6 ft by 6 ft on average.
Capacity:	240,000 tons per year ore production (1,000 tons per day).
Stope Size:	On average, each stope is 160 ft by 240 ft and 12.5 new stopes are

TABLE 2. RADON SOURCES AND EMISSION RATES FROM CASE MINE

	Radon Sources			Unit Emission Rate		Total Internal Emission
Developing Stopes (8)	Sources	Area, ft^2	Weight, tons	pCi/ft^2-sec	Ci/ton-day	Ci/day
Exposed ore surface	12,800 ft. drifts (8 stopes)	300,000	--	55	--	1.43
Muck piles	drift headings	--	160	--	2.4×10^{-3}	0.38
Developed Stopes (2)						
Exposed ore surface	6,400 ft. drifts (2 stopes)	150,000	--	55	--	0.71
Muck piles	--	--	--	--	--	--
Extracting Stopes (5)						
Exposed ore surface	half extracted stopes	190,000	--	28	--	0.45
	8,000 ft. drfts (5 stopes)	190,000	--	55	00	0.90
						1.35
Muck piles	working areas (5 stopes)	--	200	--	2.4×10^{-3}	0.48
Extracted Stopes (25)						
Exposed ore surface	25 extracted stopes	1,900,000	--	28	--	4.51
Muck piles	--	--	--	--	--	--

developed and extracted per year.

Stope Development:	On the average, there are eight stopes at various stages of development and two developed stopes ready for extraction. A developed stope has 3,200 feet of drifts (77,000 ft^2 of exposed ore surface and 115,000 ft^3 (7,200 tons) of ore removed. Drifts are of 6 ft by 6 ft on the average. Each stope being developed has, on the average, 1600 feet of drifts, 20 tons of unremoved muck piles, and 3,600 tons of ore removed. A total of 375 tons of ore are removed from eight developing stopes per day.
Stope Extraction:	On average, there are five stopes at various stages of extraction. A total of 625 tons of ore are extracted from five extracting stopes per day. At completion, 190,000 ft^3 (12,000 tons) of ore has been removed from each stope during the extraction. Each extracting stope, on the average, has 40 tons of unremoved muck piles and 1600 ft of drifts left.
Completed Stope:	On average, 12.5 stopes are completely extracted per year. There are 25 completed stopes. Each extracted stope has 76,000 ft^2 of exposed low grade ore surface primarily sills (floor) and backs (ceiling), and it has 300,000 ft^3 of void space before cavein.
Ventilation:	240,000 CFM ventilation - 1 CFM of ventilation air per ton of ore removed per year.

It must be recognized that the case mine is not a typical underground uranium mine, and its total radon emission rate is a crude approximation based on many assumptions and guestimates of radon emission rates from various sources. For a more accurate estimate of the total radon emission from an underground uranium mine, more accurate radon emission rates and more exact mine modeling are needed.

SECTION 5

RADON CONTROL TECHNOLOGY

The main objective of this study is to assess the potential options for controlling radon emission to the surface environment from underground uranium mines. Five potential radon control technologies, which have been subjected to limited experimental tests, are applied to the case mine and evaluated for their effectiveness, cost, potential problems, reliability, and equipment availability. These technologies are:

- Sealant coating on exposed ore surfaces
- Bulkheading of worked out areas (extracted stopes)
- Activated carbon adsorption of radon from highly contaminated air
- Mine pressurization
- Chemical scrubbing of highly contaminated mine air.

It should be noted that these technologies are presently in an early development phase. The assessment is based on limited publications and a great deal of engineering judgement.

SEALANT COATING FOR RADON CONTROL

The best method for controlling radon in an underground uranium mine is to prevent radon from entering the mine air. The application of a gas-tight coating over the exposed ore surface has been tested in recent years to evaluate various potential sealants.

U.S. Bureau of Mines, Spokane Mining Research Center[9-12] has screened over 65 coating materials for potential use in underground uranium mines. These materials are also screened for toxicity, flammability, and applicability in the underground mine condition. The Bureau of Mines conducted several field tests[10, 11] of the sealant application in the Dakota mine in Ambrosia Lake, New Mexico; Twilight mine in Colorado; and other mines in New Mexico. These tests involved HydroEpoxy coating of the exposed ore surface of drifts and chambers.

Lawrence Livermore Laboratory[13] has evaluated many potential sealants for possible use in underground mines. Their study involved measurement of permeation coefficients of the films and coatings and evaluation for their toxicity. Battelle Northwest[14] has also investigated the use of an asphalt emulsion sealant to contain radon from uranium tailings.

Findings of these investigations are summarized as follows:

- Under carefully controlled laboratory conditions, many sealants have extremely low permeation coefficients which will theoretically provide a better than 100:1 attenuation of radon emissions. However, the presence of so-called pinholes and the difficulty of applying a perfect coating on an ore surface reduces the effectiveness of the sealants considerably.

- Field tests suggest that water-based epoxies such as HydroEpoxy 156 and HydroEpoxy 300 are well suited for the underground mine application. A three coat system — HydroEpoxy 156, HydroEpoxy 300, preceded by Shotcrete base coating, was found to be effective in the range of 50 to 75 percent radon stoppage. Shotcrete is needed for eliminating cracks and to provide a better base for the sealants.

- The amount of sealants used varies considerably for different mines[15].

Shotcrete	-	\$0.12 to 0.72/ft^2 @ \$0.25/gal
HydroEpoxy 156	-	\$0.06 to 0.19/ft^2 @ \$7.36/gal
HydroEpoxy 300	-	\$0.12 to 0.30/ft^2 @ \$6.40/gal

- The exposed ore surface (radon source) which can be coated with a sealant is limited. Drifts through the ore body are major radon sources and best suited for the sealant coating. However, most of the drifts in a modern uranium mine are destroyed as the mining progresses. In a room-and-pillar stope mine, most drifts driven during the stope development stage are mined out (destroyed) during pillar extraction. The sealant coating applied to these drifts will thus have a limited life.

- Sealant based on an asphalt emulsion is found to be effective for stopping radon emanation from uranium tailings. Asphalt emulsion is cheap (3.5¢/ft^2)[14]. However, its applicability in an underground mine has not been tested.

Sealant Application in the Case Mine

In the case mine, the drift network in a developing stope is the only area that can be coated. Workers are not permitted to go into an extracted stope, except drifts leading to the extracted area. Haulage drifts are driven under the ore body where there is usually little or no radon emission.

Two-man coating crews will coat all the drifts in developing stopes during the third shift. Only ribs and backs (ceiling) are coated. The floor is not coated because it is covered with semi-consolidated muck. The conditions of sealant application in the case mine are as follows:

- Drifts are coated during the stope development stage. Every year 12.5 new stopes are developed and extracted. There are, on average, eight developing stopes, two developed stopes, and five extracting stopes at any time of the year.

- On the average, the coating stops 60 percent of radon emission and a coated surface has an 8-month life before being destroyed.

- Only 75 percent of the drifts in a developing stope are coated. Drifts which will be extracted shortly are not coated. Only 75 percent of the exposed surface of the drifts (ribs and backs) are coated. The floors are not coated because use of slusher will destroy the coating on the semi-consolidated muck.

- A two-man crew (third shift) uses one Shotcrete sprayer and one sealant sprayer. The crew first prepares the surface and applies Shotcrete followed with HydroEpoxy 156 and HydroEpoxy 300.

- Amounts of sealants used are:

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

Cost of the Sealant Coating

Annually, 530,000 ft^2 of drift surfaces are coated using 480,000 gal Shotcrete, 69,600 gal of HydroEpoxy 156, and 17,000 gal HydroEpoxy 300. A two-month supply of sealants is stored in the mine site.

Capital Costs

Shotcrete Machine	$15,000
Sealant Sprayer	3,000
Stored Sealant	50,000
	$68,000

Operating Costs

Materials	$298,000
Labor - Two man-years	32,000
Maintenance (equipment)	4,500
Amortization (5 years, 10% interest)	9,800
	$344,300

Sealant Effectiveness in the Case Mine Application

The sealant coating of 530,000 ft^2 per year at $344,300 ($1.45 per ton of ore removed) reduces 369 Ci of radon emitted into the mine air. This is based on average life of eight months for the coating, 60 percent reduction of radon emission by the coating, and 55 pCi/ft^2 - sec (4.75×10^{-6} Ci/ft^2 - day) radon emission from an uncoated ore surface.

The coating reduces 23 percent (1.01 Ci/day) of the radon emanation from total active stopes (4.35 Ci/day) and 11 percent of the radon from the entire mine (8.86 Ci-/day), which has 25 completely extracted stopes (600,000 tons ore mined). These figures are approximate estimates of the sealant effectiveness based on many assumptions and approximations.

Use of the sealant coating as a radon control method would require a careful mining plan so that the coating activity does not interfere with the mining activity. Effects of the presence of coating materials in the mined ore on the subsequent ore processing have not been evaluated. However, no major adverse effects are expected. All necessary equipment for application of the sealant is readily available.

BULKHEADING

Bulkheading of mined out areas such as extracted stopes is the only radon control method currently practiced in some underground uranium mines. Bulkheading is used to isolate the worked out areas and to prevent the contaminated air from these abandoned areas from mixing with fresh ventilation air and also to control the direction of air flow to the working areas.

The U.S. Bureau of Mines, Spokane Mining Research Center (16) has recently conducted a field test of bulkheading to determine the effectiveness of various types of bulkheadings and the effectiveness of a bleeder pipe used with a bulkhead. Bulkheads commonly used in the present uranium mine industry were not air-tight. The test indicated that an inorganic sealant commonly used for fire proofing (Mine-Guard) provided a better sealing. Even with the new bulkhead based on Mine-Guard, the contaminated air still leaked out around the bulkhead. Bleeding a small amount of the contaminated air from the enclosed space using a bleeder pipe stopped the leakage. The contaminated air that is bled off must be piped to a convenient lower pressure area in the return airways or an exhaust fan installed on the pipe.

When a mined out space such as an extracted stope is bulk-headed, the exposed ore surface inside the bulkheaded space continues to emit radon. The radon concentration inside the space will build up until the radon emission equals the radon decay and leakage:

$$aA = \lambda CV + CL$$

where a = radon emanation per unit area Ci/ft^2/day

A = exposed surface, ft^2

λ = decay constant, 0.181 day^{-1}

V = bulkheaded space, ft^3

C = radon concentration, Ci/ft^3

L = leakage rate, ft^3/day

For an extracted stope in the case mine with 300,000 ft^3 of extracted space, and 77,000 ft^2 of the exposed ore surface emitting 28 pCi/ft^2 - sec radon, the relationship between the leakage (or bleeding rate) and the radon concentration is as follows:

Leakage SCFM	Turnover Time Days	Radon Conc. pCi/ℓ	Percent Decayed %
0	0	118,000	100.0
30	7	66,000	57.3
60	3.6	46,000	39.2
100	2.1	33,000	28.2
180	1.2	21,000	17.7
360	0.6	11,000	9.9

If the bulkheading seals off the worked out space air-tight, then all radon will decay within the space; this will provide the most effective means of radon control. However, bulkheading alone generally does not provide air-tight seals. As the mine barometric pressure changes, the bulkheads and cracks will breathe, leaking highly contaminated air. Sometimes the leakage of the highly contaminated air can be more hazardous to the mine worker than if the bulkheading wasn't there.

Use of a bleeder pipe connecting the bulkheaded area to the exhaust ventilation system will prevent the leakage of the highly contaminated air. The bleeding creates slightly negative pressure inside the bulkheaded area which eliminates the leakage. In a later section, use of an activated carbon to treat the air that is bled off, instead of discharging into the exhaust ventilation system, will be evaluated.

Bulkhead Design

In an actual mine, a worker often has to have access to the other side of a bulkhead. A common practice is to construct a bulkhead as a temporary structure using a few pieces of lumber posts, brattice cloth, and urethane foam spray. A bulkhead used in this study has been improved over the bulkheads currently used in the mining industry, with more layers of impermeable sheets and coating.

The bulkhead shown in Figure 4 is constructed with successive layers of plywood, polyethylene sheet, brattice cloth, and coating (HydroEpoxy 300 or Mine Guard) over timber posts. The cost of the bulkhead shown in Figure 4 is estimated to be $550 each; $300 for the labor and $250 for the materials.

Bulkhead Application in the Case Mine

Sealing off a worked out area in an underground uranium mine to control radon depends on many factors which are unique to each individual mine. Some of these factors are:

- Worked out areas in some mines are used as an airway or an access to other areas of the mine. Sealing off such an area with bulkheads may require an expensive alternative airway or access route.
- In some mines, especially older ones, some worked out areas may not be accessible for bulkhead installation.
- Installation of a bleeder pipe connected to an exhaust ventilation system may be very costly.
- For bulkheading to be effective, an ore barrier may have to be left permanently between the stopes. This will reduce the ore production and, therefore, increase the ore cost per ton.

The applicability of bulkheading as a radon control technology has to be evaluated for each mine separately. Also, for a given mine, there may be many alternative bulkheading strategies. The bulkheading strategy for this study is the simplest plan in which every stope, as it is completed, is sealed in the same systematic manner.

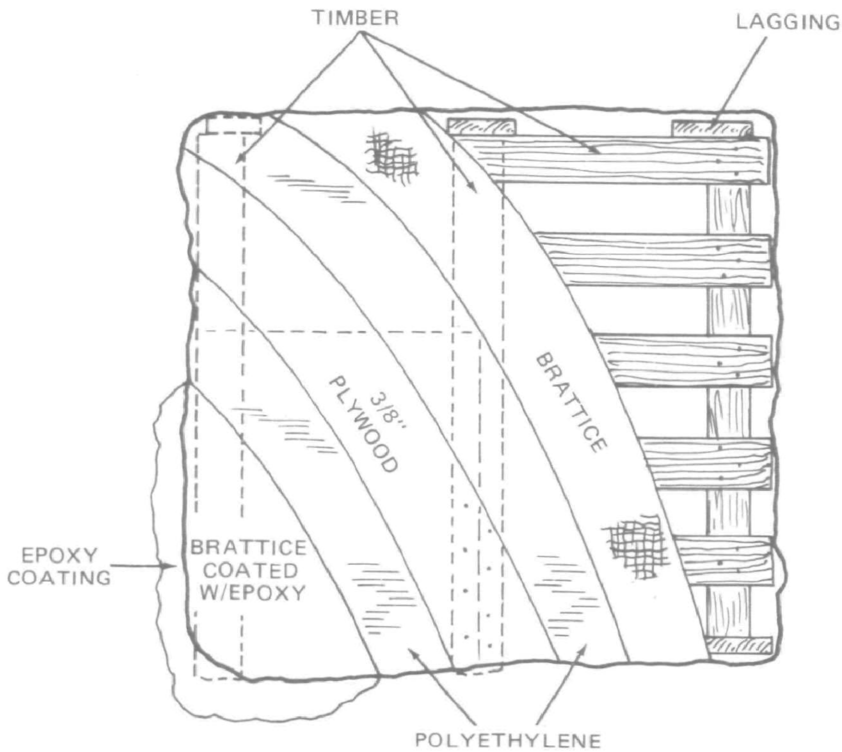

Figure 4. Schematic diagram of a bulkhead.

As each stope (shown in Figure 3) is completed, it is sealed with eight bulkheads (six for drifts and two for raises). Each completed stope has 12 drifts connecting to adjoining stopes. Each new stope is connected to one completed stope. This is based on an assumption that stopes are lined one after the other, and a new stope touches on one side of the completed stope. Bulkheads for raises are expected to be different from those used for drifts, but for simplicity, the same costs are assumed for all bulkheads. The contaminated air inside the bulkheaded area is bled out at the rate of 100 CFM from each sealed stope.

Selection of the 100 CFM bleeding rate has no basis other than that it is close to an upper limit, if the bled air from each stope is treated by an activated carbon adsorption system (this is discussed in a later section). Further investigation of bulkheading is required to determine whether the 100 CFM bleeding rate is sufficient to create the necessary negative pressure in a completed stope, or if a lower rate may satisfy the requirement.

Sealing off one stope of the case mine using eight bulkheads and 100 CFM bleeding, will divert 0.18 Ci/day radon from potential contamination of the mine air and discharge only 0.13 Ci/day radon to the surface environment. The remaining 0.05 Ci/day is decayed in the sealed stope.

<u>Cost and Effectiveness of the Case Mine Bulkheading</u>

Annually, 12.5 stopes will be sealed using 100 bulkheads. Each sealed stope is connected to the exhaust ventilation system by 1000 feet of 6-inch PVC pipe (guestimate). It is also assumed that 100 CFM of the contaminated air in the sealed stope will be bled out into the exhaust system. The annual costs are summarized as follows:

Material & Labor	
Bulkheading	$55,000
Piping	12,000
	$67,000
Maintenance	
@ 20% of Material & Labor	13,400
TOTAL	$80,400

The systematic bulkheading of 12.5 stopes per year with 100 CFM bleeding from each stope will divert 2.25 Ci/day radon from the mine air and discharge only 1.62 Ci/day to the surface environment. The bulkheading eliminates 0.63 Ci/day radon by letting it decay in the sealed stopes. The bulkheading system cost is 80,400 per year ($0.34 per ton of ore removed).

The estimated effectiveness of the case mine bulkheading is an approximation based on many crude assumptions. However, it is apparent that the bulkheading is a very effective means of diverting the contaminated air from the underground mine workers, and it also reduces the radon emission to the surface environment by letting some of it decay inside the bulkheaded area.

Potential Problems and Solutions

Bulkheading for radon control must consider the danger of potential exposure of very high radon concentration by the mine workers. A bleeder pipe connecting the bulkheaded stope to the exhaust ventilation system or a radon removal system must be installed.

If a mine worker has to go into a bulkheaded stope, the stope has to be either decontaminated by venting it, or the miner must use an approved respirator with charcoal canister.

The mining plan must consider bulkheading at a very early phase and include design of the ventilation and mining system to accommodate the bulkheading. The mining system must be planned to minimize the need for a mine worker to go into a bulkheaded stope.

RADON ADSORPTION ON ACTIVATED CARBON

There has been limited research and development work on adsorption of radon by activated carbon.[17-22] Findings of these investigations can be summarized as follows:

- Radon gas can be adsorbed from air by various activated carbons.
- The capacity of a given carbon to adsorb radon depends on volumetric flowrate of air only and not on radon concentration.
- The capacity of a given carbon to adsorb radon depends strongly on temperature, as shown in Figure 5.
- The capacity of a given carbon to adsorb radon is reduced by the moisture in the air (Table 3).
- To maximize carbon bed utilization, air velocities should be as low as possible. Air velocities between 0.5 and 2.5 lit/cm^2-min have been suggested.

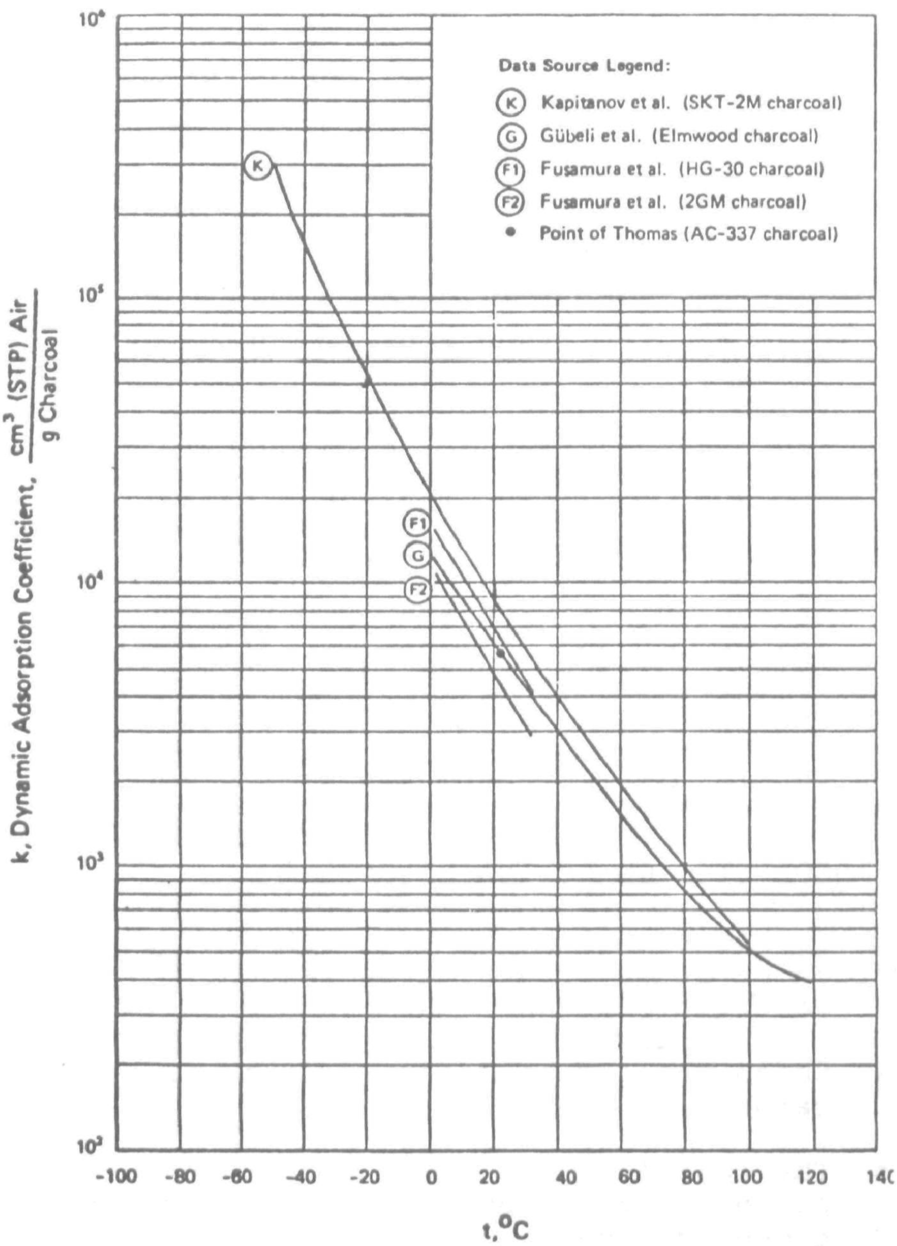

Figure 5. Effects of temperature on activated carbon adsorption of radon (22)

TABLE 3. RADON ADSORPTION ON VARIOUS CARBONS

Type of Carbon	Temp. °C	Adsorption Capacity* cc of Air/g Carbon		Ref.
		Dry Air	Humid Air (100%)	
SKT-2M	18	9650	4450	19
N°2	18	6300	2100	19
SKT-1	18	9200	NA	19
MSKT	18	7400	5250	19
Sutcliffe-Speakman 207 C	25	3530	NA	15
Norit RFL 3	25	4610	NA	15
Norit RFL 111	25	4660	NA	15
Ultrasorb	25	5000	NA	15
Pittsburgh PCB	25	5690	NA	15

* Adsorption Capacity represents the air volume per gram of Carbon before radon breakthrough.

Concept and Design Basis

Mine air of high radon concentration is extracted from a closed-off area of the mine, such as a bulkheaded stope, and passed through an activated carbon system to remove radon. This creates a negative pressure in the closed-off area and prevents contamination of the ventilation air by high radon air from the closed-off area.

Presently available information is not sufficient for the design of a full-scale carbon facility. The design basis used in this study is based on available information and engineering judgement. Some process requirements are discussed briefly as follows:

- The carbon system will be sized for 100 CFM air flow. The 100 SCFM flowrate requirement approaches the upper limit for the acceptable size of an underground carbon adsorption unit, as will be seen later. It also represents a two-day air turnover time for a typical 10' x 160' x 240' completed stope and approaches "typical" bleed-off flowrates considered by investigators. The negative pressure generated in the closed-off area will depend on various other factors such as bulkhead and type of rock formation.

- The radon contained in the bleed stream is captured by activated carbon and allowed to decay underground.

- Because of the rugged mine environment, automation should be kept to a minimum. The unit should be able to operate unattended for 24 hours. Interruption through utility stoppages should not cause safety problems.

- The carbon adsorption unit should be simple to install and operate. It should be able to withstand rough handling during installation and operation.

Description of Proposed Carbon System

For this study, each bleeder pipe from a sealed stope is provided with one modular unit of the activated carbon adsorption system. There will be 12.5 modules installed per year for 12.5 completed stopes, each treating 100 CFM of the contaminated air.

Many flow schemes can be considered for the radon adsorption on carbon. Three schemes are discussed here. One of these schemes, which appears to have an advantage over others (Carbon System #1), will be studied in greater detail to identify operational problems and allow cost estimation.

Carbon System #1--

Carbon System #1 (Figure 6) consists of two carbon adsorption systems in series. A small flow of air (100 SCFM) is bled off from a bulkheaded area of the mine (completed stope). The air is filtered in order to remove dust particles and radon daughter products.

Radon is then adsorbed in a carbon column, sized to allow at least 24 hours of unattended operation. Once a day, the carbon column is regenerated using hot air. After cooling and removing condensed water, the contaminated air from regeneration is sent through a second carbon column to adsorb, once again, the radon gas, this time utilizing considerably less carbon. The second column is designed to allow self-regeneration by decay of the radon. Moisture build-up may be a problem in the second column and occasional drying may be required.

Carbon System #2--

If moisture in the air proves to be a major problem, a system such as shown in Carbon System #2 (Figure 7) may be considered. Since the first carbon column is regenerated daily, moisture is also removed from the column. Most of the moisture from regeneration is removed after cooling in the heat exchanger. The remaining moisture is then removed in a desiccant column (lithium chloride, silica gel, activated alumina or molecular sieves) thereby enhancing the carbon adsorption and preventing moisture build-up in the second column. The desiccant may be placed in front of the first carbon bed. This increases the capacity of the carbon bed, but requires more water to be removed by the desiccant.

Carbon System #3--

Radon adsorption capacity on carbon is enhanced drastically by a reduction in air temperature. This principle is used in Carbon System #3 (Figure 8). Air is dehumidified and cooled to -40°C. This allows operation of a single carbon column only. The column is designed so that it will autoregenerate through radioactive decay of radon.

Carbon System on the Surface--

An alternative to installing many underground carbon systems treating the contaminated air from bleeder pipes connected to worked out stopes, is to collect all contaminated air from these bleeder pipes and treat them in a large carbon system located at the surface. The concept of treating contaminated air in a large carbon system located at the surface was suggested by A. D. Little[22].

Carbon Adsorption System for the Case Mine

In addition to the three systems briefly described before,

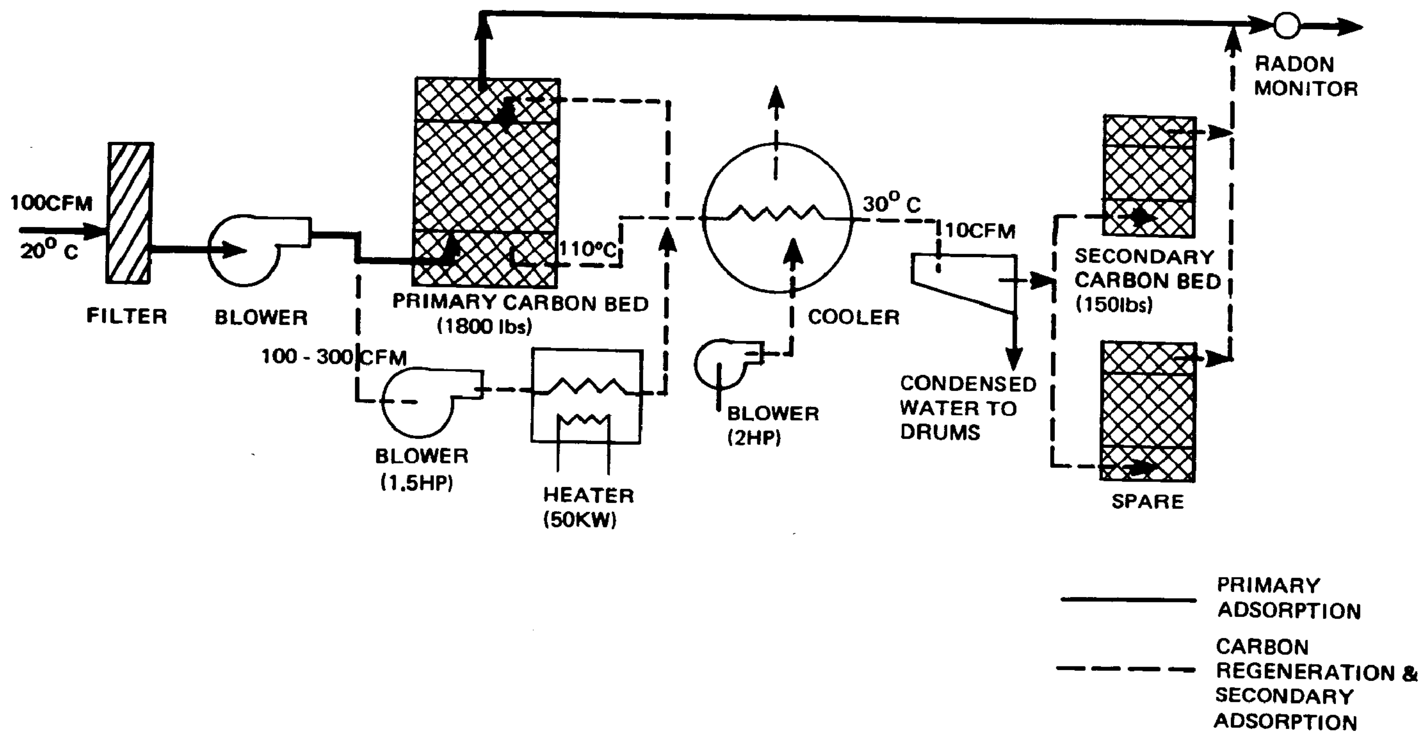

Figure 6. Radon removal from mine air by carbon adsorption - System 1.

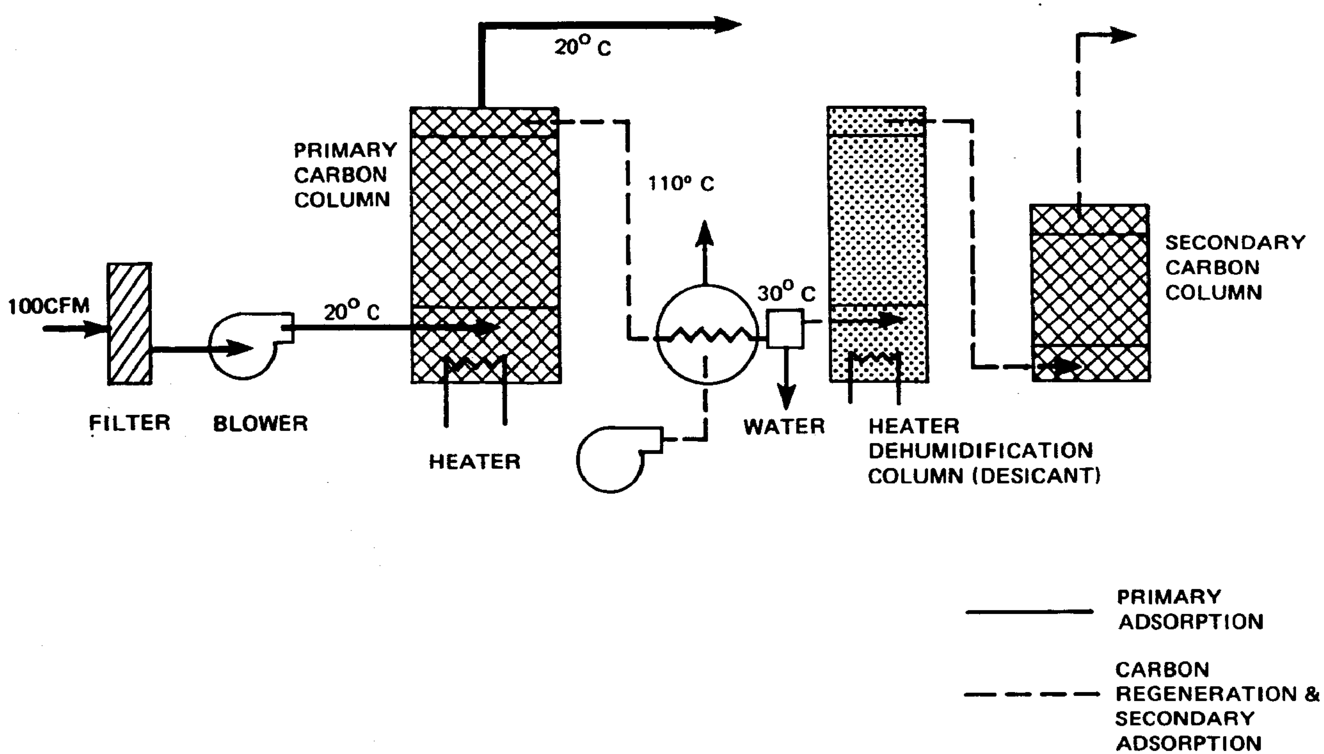

Figure 7. Radon removal system from mine air by carbon adsorption - System 2.

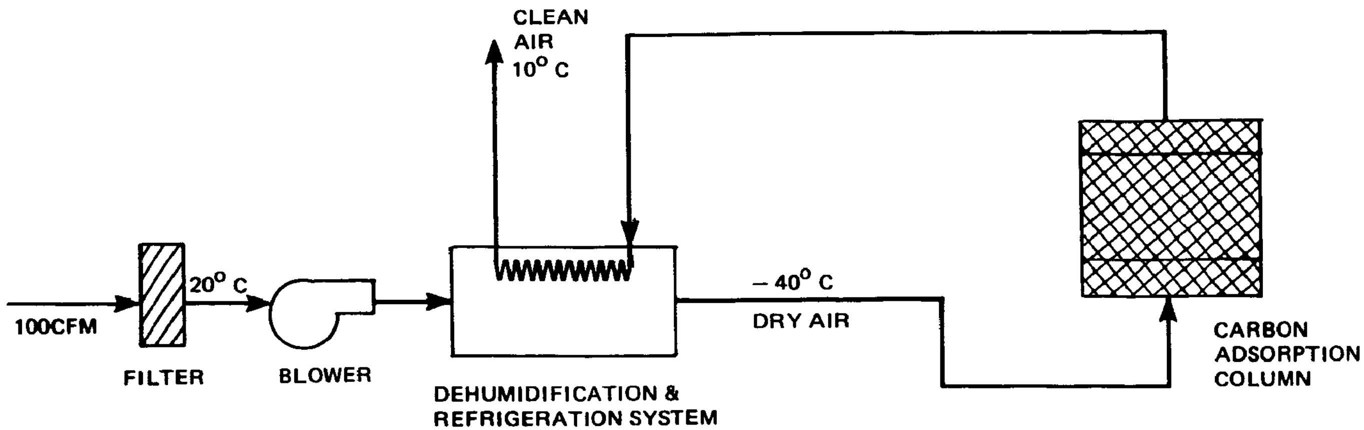

Figure 8. Radon removal from mine air by carbon adsorption - System 3.

many other flow schemes are possible. The selection of an adsorption system for a full-scale facility will have to be made considering a number of criteria such as:

- Simplicity and ruggedness - compatible with the mine environment
- Weight and size limitations to satisfy underground mine installations
- System effectiveness
- Maintenance requirements and reliability
- Utility requirements
- Safety
- Cost.

Although presently available information is not sufficient for selection of the most optimum system, Carbon System #1 appears promising, simple, and perhaps least costly (see appendix for design criteria).

As shown in Figure 5, in the selected carbon system, contaminated air from a bulkheaded stope is filtered to remove dust particles and daughter products. It is then sent through carbon column #1 utilizing a variable speed blower. Carbon column #1 (four feet in diameter and five feet in height) is designed to operate 24 hours without regeneration. The treated air is monitored continuously for radon concentration. The treated air may be piped into the returning exhaust air system. Incoming contaminated air is analyzed once a day.

After 23 hours operation, the carbon bed #1 is regenerated utilizing a 75 kW external electrical air heater. A 300 SCFM nominal flow of air is heated to approximately 250°C and sent through carbon bed #1 counter-currently in a recirculation mode. Recirculation of the hot air through the carbon bed allows the bed to heat up to 110°C. When the desired bed temperature has been reached, the recirculation rate and power input are reduced as required. Hot air is drawn off from the primary carbon system in a repeated purge and refill manner and sent through a finned tube, air-to-air heat exchanger, and water trap. The condensed water, contaminated with radon, is stored in a drum and allowed to decay. The cold (30°C) bleed stream from the water trap is directed through a smaller carbon column for adsorption of radon. Carbon bed #2 contains 150 lbs of carbon. A 55 gallon drum can be used. Carbon bed #2 can take radon charges of the 20 regeneration air, assuming no radon decay. Since the radon half-life is 3.8 days, carbon bed #2 will last indefinitely. When all the radon is desorbed from carbon bed #1, the heater is turned off, and cold ventilation air is blown through carbon column #1 as required to lower the bed temperature. The total regeneration cycle will take approximately one hour. During a week-end, the carbon system may be shut off.

Since moisture may have an adverse effect on adsorption of radon, the second bed may have to be "dried" occasionally. A spare column is, therefore, installed to be used when radon in column #2 is allowed to decay prior to the "drying" operation. Carbon beds, especially carbon bed #2, will be loaded with the radon daughters; primarily lead-210 (weak gamma and beta emitter). When it is no longer usable, it may be buried in a secured section of a completed stope.

Radon release in the exit stream is monitored continuously by a device such as developed by Franklin et al [23]. The monitor consists of a scintillation chamber, a photo multiplier, an amplifier, and a window circuit that screens out the low-level pulses and noise. It provides continuous monitoring and recording. The inlet radon concentration is measured once a day prior to regeneration operations utilizing the same devices.

Safety precautions should be taken to protect the mine workers. Additional radon monitoring equipment may need to be installed nearby the adsorption system to alert the miners in case of system malfunctions. The miners should also be protected from γ-ray emissions through proper positioning of the carbon columns or through shielding. Carbon column #2 could conceivably be located behind the bulkhead. A list of the major equipment required with approximate cost is shown in Table 4.

Cost and Effectiveness of Activated Carbon System

An average 12.5 activated carbon system, each treating 100 CFM, will be installed per year to treat the contaminated air from the sealed stopes. The capital and operating costs for each unit are summarized as follows:

Capital Cost of Each Unit

Major equipment	$22,000
Auxiliaries & Installation	11,000
	$33,000

Annual Operating Cost of Each Unit

Material (carbon, fitters, piping)	$ 1,000
Utilities (25,000 kwh @ 4¢/kwh)	1,000
Labor (0.25 man-year)	8,000
	$10,000
Amortizing (on avg. 5-yr life, 10% interest)	8,700
TOTAL	$18,700

TABLE 4. MAJOR EQUIPMENT LIST OF CASE MINE CARBON SYSTEM

Major Equipment	Specifications	Cost*
Carbon Bed #1	4' x 5' Carbon bed/1800 lbs Carbon	$ 4,000
Carbon Bed #2	55 gallon drum; 150 lbs Carbon	500
Spare Carbon Bed	55 gallon drum; 150 lbs Carbon	500
Electrical Heater	75 kW; Stage Controller	4,000
Heat Exchanger	Finned tube; 555 sq. ft. bare basis	9,000
Radon Monitor	Custom Design	4,000
TOTAL		$22,000

*Approximate purchased equipment cost.

The activated carbon system is used in conjunction with the bulkheading strategy; that is, the activated carbon system treats the bled air from the sealed stope. Each carbon system treats 100 CFM of the contaminated air with 0.13 Ci/day radon. The carbon system is expected to remove 95 percent or more of radon.

On average, 12.5 carbon units are installed per year at the total cost of $412,500. A total of 563 Ci of radon will be removed by 12.5 carbon units at the annual operating cost of $233,750 ($18,700 for each unit).

A carbon system installed in a completed stope has to be operated continuously until the mine is shut down. Some carbon systems installed in the early phase of the mine will be operated for longer than those installed later. If an average operating life of five years is assumed for all carbon systems, each carbon system will cost a total of $83,000 to install and operate for five years. This represents $4.32 per ton of ore produced. Each carbon system removes 45 Ci of radon per year, and it will remove 225 Ci over the five-year life of the carbon system.

Assessment of the Case Mine Carbon System

Based on experience with krypton and xenon adsorption on activated carbon and on preliminary radon adsorption tests, radon adsorption on activated carbon appears technically feasible, utilizing commercial carbons and standard equipment. Application of this technology should be considered in combination with other approaches such as bulkheading. Assessment of the activated carbon system applied to the case mine is summarized as follows:

- The carbon system is an integral part of the bulkheading strategy. Since the cost of the carbon adsorption treatment depends strongly on the air flow rate, the bleed rate should be minimized. This minimum rate depends on geologic conditions, bulkhead construction, and atmospheric conditions.

- Removal of radon from the contaminated air by activated carbon adsorption, instead of dilution by forced-air ventilation, will reduce total ventilation requirements and, therefore, there may be a net economic benefit, particularly for deep mines. This reduction in ventilation air cannot be quantified at present.

- Operation of a carbon adsorption system is foreign to uranium mining operations, and skilled operators may, therefore, have to be hired or trained. Such skills are often not available in mining types of communities.

- While maintaining a negative pressure behind a bulkhead, the 100 SCFM bleed stream also extracts approximately

78 percent of the radon emitted into the completed stope. Nearly all (>95 percent) radon is adsorbed on the carbon and allowed to decay while adsorbed.

- Potential safety problems associated with the adsorption system should be given additional attention. All eventualities, such as interruption in electrical service and any potential malfunctions, should be studied. Adequate alarm systems should be installed. Workers should be protected against γ-ray emissions from radioactive decay. Carbon column #2 could be installed behind the bulkhead or shielding can be used. Fire extinguishers should be available.

- The carbon adsorption system itself requires additional developmental work prior to design of a commercial unit:

  -- Activated carbon best suited for the radon adsorption service should be selected. The radon adsorption capacity, the effect of moisture, should be determined experimentally.

  -- Appropriate regeneration procedures need to be developed. Heat and temperature requirements need to be determined. The volume of regeneration air should be minimized. Carbon aging should be studied.

  -- Prototype adsorption units should be tested under various field conditions.

MINE PRESSURIZATION FOR RADON CONTROL

Radon gas inside the ore body diffuses out into the mine through an interconnecting pore structure by molecular diffusion, convective flow, or both. The driving force for molecular diffusion is the radon concentration difference between the rock interstitial space and the mine atmosphere. The driving force for convective flow is a pressure gradient. The molecular diffusion is a relatively slow process compared to the convective flow of radon contaminated air through the pores.

Mine pressurization has been suggested for controlling radon emissions into the mine air by providing a convective flow into the ore body. Limited experiments have been conducted to study the effects of mine pressurization on radon emissions into the mine. Schroeder, et al.[24] conducted experiments in 1963 and 1964 at Lake Ambrosia, NM. They found that applying a 1 cm Hg of overpressure on a section of the mine would reduce the radon emission approximately ten-fold.

Subsequently, the Bureau of Mines[5,9] has tested the over-pressurization technique in various mines with mixed results. Switching from a blowing to an exhausting ventilation system doubled the radon concentration in one of the stopes in the Dakota mine, whereas only a 20 percent change was observed in the Laguna, NM mine. Tests conducted at the Twilight mine[5] indicate that a differential pressure of 0.02 inch water across the bulkhead of a stope reduces the radon concentration in the stope by more than 90 percent. No information is provided with respect to the ultimate fate of the radon which has been removed from the ventilation air.

For the mine pressurization to work, an air "sink" into which the air can flow is required. This may be the surface atmosphere. If the ore body, however, is surrounded by an impermeable barrier, convective flow of air into the ore body will stop in a short time, regardless of the mine pressure, and the radon emissions into the mine atmosphere will return to the non-pressurized condition[2].

Some preliminary experiments have been conducted by the Bureau of Mines in a Kerr-McGee mine for testing mine pumping[5] concepts. The intent is to provide a large negative pressure inside the mine during off-shift hours, utilizing an exhaust fan, thereby extracting large quantities of radon from the ore bodies and then releasing the vacuum during on-shift hours. It is thereby assumed that back-flow of air into the rock during working hours will significantly reduce radon emissions. Results so far, however, have been inconclusive. It is unlikely that total radon emissions to the surface will be reduced by this technique.

Many questions still remain with respect to radon control by mine pressurization, particularly as relate to the air sink and permeability of the gas flow.

- If the ore body and host rock are impermeable to gas flow, or if some other flow barrier exists, mine pressurization will only have a temporary effect on radon emissions into the mine.

- If the ore formation has an adequate permeability and extends all the way to the surface, radon control in the mine by mine pressurization is a distinct possibility. However, the permeability has to be such that gas flow is slow to allow decay of radon before reaching the surface environment.

<u>Designs of Mine Pressurization</u>

Mine pressurization can be pressurization of the entire mine or pressurization of a selected area within the mine, or a combination of the two. An alternate technique, called mine pumping, has also been considered[5].

Total Mine Pressurization--

In pressurization of the entire mine (Figure 9), a downcast fan located on the surface is employed rather than an upcast exhaust fan system normally used. The air intake is provided through a ventilation shaft. The overpressure in the mine depends on the pressure drop through the mine. If a higher pressure is needed, a restriction can be placed in the exhaust vent hole.

To convert a mine from an upcast exhaust ventilation to a downcast ventilation, the following additional expenditures would be required:

- Reinstallation of fan
- Additional vent hole
- Air lock
- Additional fan
- Connecting drifts.

There may also be additional power requirements, depending on the pressure to be used in the mine. The cost of pressurizing a mine depends on many variables such as:

- Mine ventilation layout
- The desired pressure and air flowrates
- The desired reduction in radon emissions.

In view of the undefined nature of this technology and the hypothetical nature of the case mine, it is meaningless to speculate on the cost for pressurizing the case mine.

Stope Pressurization--

Pressurization of a stope is accomplished using a booster fan located at one of the raises. The booster fan takes fresh air from a haulage drift and blows it into the stope at slightly higher pressure. Pressurization of a working stope might require:

- Bulkheads
- Closeable doors
- Additional drifting

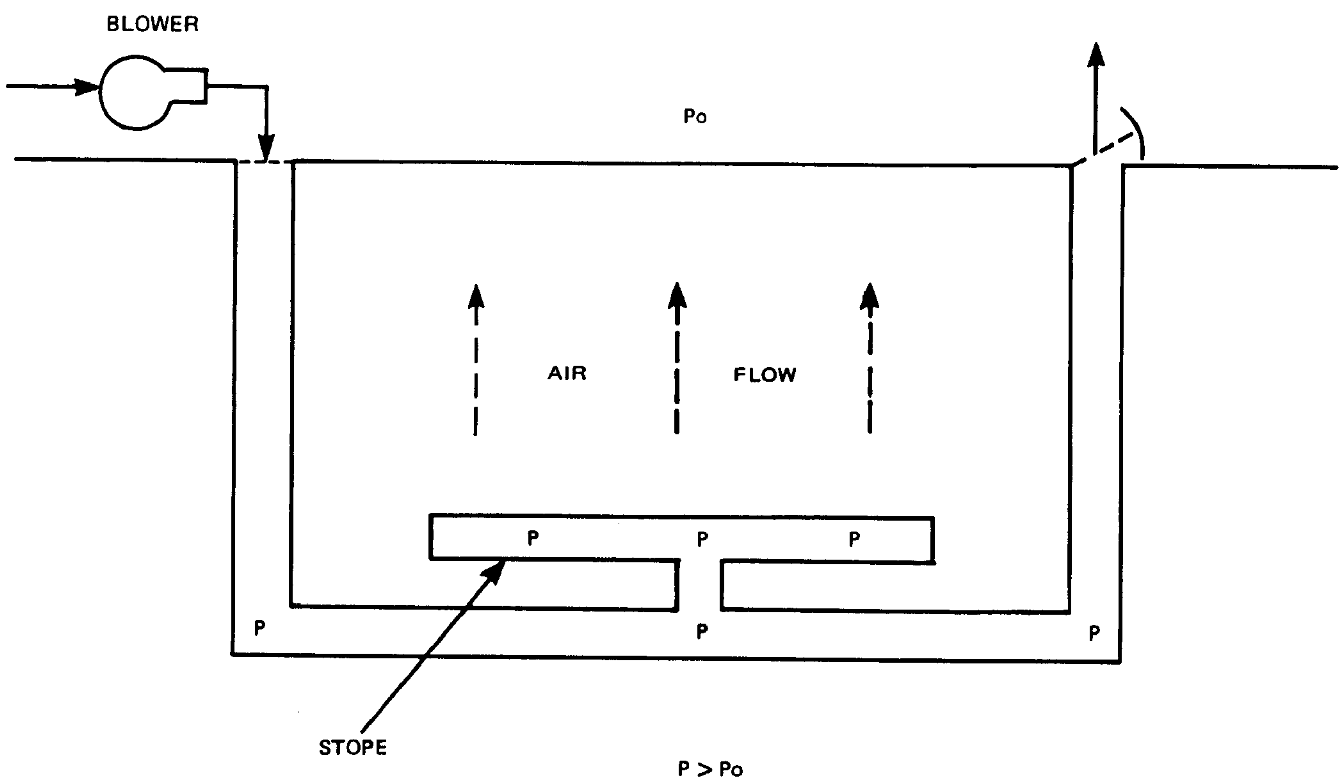

Figure 9. Schematic diagram of mine pressurization.

- Additional vent tubing
- Fan and auxiliaries.

<u>Assessment of Mine Pressurization</u>

Based on the available literature, it appears that mine pressurization may be a viable method to reduce radon emissions into the mine atmosphere depending on geological factors. However, the effectiveness of mine pressurization in reducing radon emission into the mine air and also to the surface environment, cannot be quantitated at the present time. More study is necessary to evaluate the effectiveness of mine pressurization for radon control. The study should include detection of the change in the radon emission from the surrounding surface environment in addition to that in the mine atmosphere.

The mine pressurization is expected to have different results for different mines. An actual test will be the only means of determining the effects of pressurization for any particular mine.

The equipment necessary for pressurizing an entire mine or a working stope is readily available.

Pressurizing a mine will have little effect on working conditions in the mine, except the presence of air locks, which will require a special evacuation plan for underground workers. Haulage through air lock doors slows down the tramming operation and increases maintenance costs.

MISCELLANEOUS RADON CONTROL TECHNOLOGY

The concept of removing radon from radon-contaminated mine air by reacting it with strong oxidizing agents, such as bromine trifluoride (BrF_3) and dioxygenyl hexafluoroantimonate (O_2SbF_6), have been investigated by Argonne National Laboratory[25-31]. Their findings are summarized as follows:

- Liquid oxident bromine trifluoride (BrF_3) is very effective in oxidizing radon from the contaminated mine air. The reaction product of radon is nonvolatile ionic compound. A liquid scrubber may be used to react radon with the oxidant. However, the oxidant is very corrosive, toxic, and unstable especially in the presence of water vapor. The scrubber will probably require corrosion resistant material and dehumidification of the air before scrubbing to minimize the oxidant consumption.

- Solid oxidant, dioxygenyl hexafluoroantimonate (O_2SbF_6), reacts rapidly with radon gas, forming a nonvolatile radon compound; hence, it can be used for purification of radon-contaminated mine air using an absorption bed concept. However, in the presence of moisture the oxidant is highly corrosive, toxic and unstable. The absorption system will require a pretreatment of dehumidification and a special corrosion resistant material.

- These concepts are still in a laboratory investigation stage. Many more laboratory tests and pilot plant investigations are required to determine chemical consumption, side reactions, reaction products, handling property of the reactants and product, types of equipment, equipment construction materials, and design parameters.

Although the concept of radon removal by reacting it with a strong oxidant appears technically feasible, the corrosive and toxic nature of the reactants make their applicability in an underground uranium mine questionable.

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APPENDIX A

DESIGN CRITERIA OF ACTIVATED CARBON SYSTEM FOR RADON REMOVAL

OVERALL SYSTEM

- Flowrate: <100 SCFM
- Air Temperature: $20^{o}C$
- Air Relative Humidity: 100 percent
- Radon Removal Required: >95 percent
- Adsorption - Desorption Cycle for Column #1
  - Minimum 23 hours adsorption
  - One hour desorption time
- Adsorption Column #2: At least 95 percent decay of radon
- Radon monitoring required for treated air
- Radon alarms required
- Unattended system operation for at least 24 hours
- Provision for γ-ray protection for workers

PRIMARY CARBON COLUMN

- Design adsorption capacity of carbon: 6,000 cc/g (100 percent humidity, $20^{o}C$)
- Adsorption layer: 10 cm for 0.5 lit/min-cm^2
- Carbon bed: 4 feet diameter
- Length of bed: 5 feet
- Carbon needed for 23 hours: 780 kg
- Carbon in bed: 820 kg

HEAT REQUIREMENTS FOR REGENERATION (PER CYCLE)

- Bed heat-up (20°C to 110°C): 90,000 Btu
- Moisture removal: 160,000 Btu (maximum)
- Total (maximum): 250,000 Btu/cycle

Heat is supplied by a 75 kW external electrical air heater. Air is recirculated through the bed until the appropriate temperature level is reached. Heating elements in the bed are not practical because of the low thermal conductivity of carbon and the potential for local overheating. Air temperatures should not exceed 250°C.

HEAT EXCHANGER - COOLER

- Load (maximum): 250,000 Btu/Hr
- Heat Transfer Coefficient, U = 6.5 Btu/hr ft^2 °F
- LMTD = 70°F
- Area: 555 sq. ft. (bare tube basis)
- Assume steel, finned tubes

SECONDARY CARBON COLUMN

- Design adsorption capacity of carbon: 3,000 cc/g carbon
- Purge gas during regeneration: 250 cubic feet
- Carbon bed: 150 lb drum, 20-day life with no decay.

GLOSSARY

case mine: The hypothetical mine selected for this study.

curie (Ci): A source of radionuclide which undergoes radioactive decay of 3.7×10^{10} disintegration per second.

cut-and-fill stoping: A stoping method in which the ore is excavated by successive flat or inclined slices, working upward from the level. After each slice is blasted, all broken ore is removed, and the stope is filled with waste before the next slice is taken out.

developing stope: Stope in which development drifts are being driven to gain access to ore.

drift: A horizontal opening in or near an ore body and parallel to the course of the vein or the long dimension of the ore body.

drift surface: Exposed surface of drift.

extracting stope: Stope in which the ore is being extracted.

haulage drift: Drift developed for movement of men, supplies, waste, and ore.

HydroEpoxy 300: Two component, water base epoxy manufactured by ACME Chemical & Insulation Company.

half-life of radon: Time in which a half of radon will decay.

muck: Ore broken in process of mining.

ore: Mineral of sufficient value as to quality and quantity which may be mined with profit.

ore body: Mineral deposit that can be worked at a profit.

orepass: Vertical or inclined passage for the downward transfer of ore.

picocurie (pCi): 10^{-10} curie; 0.037 dis./sec.

raise: Vertical or inclined opening driven upward from a haulage level to the ore level.

ribs of drift: Side of a pillar or the wall.

room-and-pillar stoping: Stoping method in which the ore is first mined in rooms and then ore in the pillars is subsequently mined.

Shotcrete: Pneumatically applied portland cement mortar.

slusher: Mechanical dragshovel loader.

stope: Unit excavation from which ore is being, or has been, excavated in a series of steps.