APPENDIX III

ENGINEERING CONTROL METHODS

A. Introduction

This appendix contains examples of engineering control methods that can be used to reduce miners' exposure to radon progeny in underground uranium mines, although the same methods are applicable to other hard rock mines. Many of these control methods have been traditionally used in uranium mines, yet only recently have researchers (primarily from the Bureau of Mines) studied the efficacy of these methods [Bates and Franklin 1977; Bloomster et al. 1984a, 1984b; Franklin et al. 1975a, 1975b, 1977, 1981, 1982; Steinhausler et al. 1981].

B. Mechanical Ventilation

Mechanical ventilation is the primary and most successful technique for reducing exposure to radon progeny. Average measurements of 2 to 200 working levels (WL) of radon progeny were common in U.S. uranium mines during the early 1950's before mechanical ventilation became prevalent [Lundin et al. 1971]. In contrast, during 1979 and 1980, the average concentrations of radon progeny recorded by MSHA ranged from 0.30 to 0.46 WL in the production areas of 61 underground uranium mines [Cooper 1981]. Thus the concentration of radon progeny in U.S. uranium mines has been greatly decreased, mainly because of improved ventilation. Sweden has also successfully reduced radon progeny concentrations in mines with improved mechanical ventilation; the average annual exposure for nonuranium miners in Sweden decreased from 4.7 working level months (WLM) in 1970 to 0.7 WLM in 1980 [Snihs 1981].

1. General Principles

Dilution ventilation in large mines consists of primary and secondary ventilation systems. In the primary system, fresh air is brought into the mine either through separate air shafts or through mine entrances used for miner access and equipment transport. The air can be blown in by a fan located at the surface or drawn in by a fan located inside the mine. Once in the mine, the air is blown or drawn through the main active passageways and then is pushed or drawn out of the mine through special ventilation shafts or openings used to remove ore.

The secondary or auxiliary ventilation system provides fresh air to miners working in areas that include stopes and faces where access comes from a single shaft or drift and thus the work area is a dead end. For these areas, the air is often removed through the same shaft that was used to bring in the air. The source of fresh air for the secondary system is provided from the primary air system in the main passageway.

To prevent mixing fresh air and contaminated air in the shaft or drift leading to the dead end, the secondary system usually consists of ductwork with a fan to blow or exhaust fresh air from the main passageway to the face. The contaminated air then passively returns to the main passageway (because of a pressure gradient) through the shaft without contaminating the supply air. The contaminated air at the stope may also be brought back to the main passageway through a second duct and fan system. Once returned to the main passageway, the contaminated air joins the primary exhaust air stream which is then carried out of the mine.

2. Designing a Dilution Ventilation System

Ventilation requirements must be considered when planning and designing the mine. Adding mine ventilation as an afterthought once the mine has been designed or completed is usually more expensive and less efficient. Consideration should be given to the following when designing the ventilation plan for a mine [Ferdinand and Cleveland 1984; Bossard et al. 1983]:

- Identify the outline of the ore body that will be mined;
- Determine the rate of emanation of radon from the rock in which the ore occurs;
- Place as much of the primary ventilation system as possible including entrances and passageways in barren ground (i.e., ground not containing ore);
- Set up passageways so that a split or parallel system of ventilation can be used;
- Set up the mine so that working faces ventilated in a series are minimized;
- Design the mine so that air inlets are located on one side of the ore body and exhaust airways on the opposite side of the ore body;
- Design the mine so that the distances ventilation air travels in the mine are minimized (reduce or eliminate reentrainment and short circuits);
- Design the mine so that adequate volumes of air can be provided without having high pressure drops across air controls in haulage and production areas;
- Design the ventilation system to account for increasing concentrations of radon gas, and therefore radon progeny, since as the mine ages there will be more surface area for gas exchange into the mine; and
- Consider control devices, fans, push-pull systems, and minimizing leaks when designing the system.

3. Primary Ventilation System

The primary ventilation system delivers fresh air for the secondary air system and removes contaminated air from the secondary air system. The design of the primary air system is discussed in the following paragraphs.

a. Split or Parallel Ventilation Systems

A "split" or "parallel" ventilation system involves providing all or just a few working areas with fresh air that has not been previously used to ventilate other working areas. After the working areas are ventilated, the air is then pushed or drawn back into the primary system where it is moved out of the mine. By contrast, in a "series" ventilation system, all areas are ventilated by a single continuous air circuit.

The advantages of a split or parallel system include the reduction of both the residence time and cumulative air contamination [Ferdinand and Cleveland 1984]. A series system, on the other hand, has several disadvantages. In addition to its long residence air times and a cumulative build-up of air contaminants from one area to another, other disadvantages include the following:

- High air velocities which are often required;
- Higher power costs associated with moving air at high velocities because of increased static pressures, unless additional ventilation shafts are constructed [Rock et al. 1971]; and
- The potential spread of toxic gases to all areas of the mine in the event of a fire.

However, to keep residence time down in a split or parallel ventilation system, the air velocities to the multiple drifts must be maintained. This will increase the fan and power requirements; additional ventilation shafts may also be necessary.

b. Control Devices

Sliding door regulators are used to prevent air from passing where miners and equipment need to pass through periodically. The problem with doors is that to be effective they must be closed after being used. Doors must also be well-constructed to remain secure with repeated usage; steel doors in substantial frames are most commonly used in Canada [Rock and Walker 1970].

c. Pushing Versus Pulling Ventilation Systems

The pressure on the air intake side of a mine is always greater than on the exhaust side regardless of whether a pushing or pulling ventilation system is used. The difference is that the intake side pressure is greater than atmospheric pressure for a pushing system, whereas in an exhaust or pulling system, the pressure on the intake side is below atmospheric pressure.

Exhausting (pulling) offers some advantages over a pushing system. For example, forcing air into haulageways and escape areas often requires air locks and other equipment. Exhaust systems draw air from these locations without the need for air locks and remove air from the mine through special airways to exhaust fans.

4. Secondary (Auxiliary) Ventilation System

The secondary (auxiliary) ventilation system brings sufficient fresh air to the working area from the primary air system without mixing it with the returning contaminated air from the face.

a. Use of Ducts

The use of compressed air from pneumatic equipment is not recommended for ventilating working faces because insufficient air is supplied, the air discharge location cannot be controlled, and excessive dust is often created [Rock et al. 1971]. Thus a duct must be used in the tunnel leading to the active face to separate fresh from contaminated air. Sometimes two ducts are used, one to supply air to the face and another to remove contaminated air. Air can be either pulled or pushed into the work area, or a combination of the two.

b. Blowing Duct System (Push System)

The most widely used type of secondary ventilation consists of pushing air through a duct in the access tunnel by means of an auxiliary fan located in the primary air system [Rock et al. 1971]. To be effective in ventilating the face, the end of the duct should come within 25 to 30 feet of the face discharging 2000 cubic feet per minute (CFM) [Bossard et al. 1983]. The duct must be properly placed so that the entire work area is swept with the fresh air.

The advantage of pushing air is the large contaminant dilution ventilation provided directly in the miners' work area. The air stream will blow across the face because approximately 10% of the duct exit velocity will still exist at a distance equal to 30 duct opening diameters from the duct opening [ACGIH 1984]. The disadvantages include the generation of dust due to the high air velocity needed to blow clean air over the entire working face and the return of contaminated air through the access tunnel used by miners on their way to and from the work area.

Another advantage of an air-blowing system is that it increases pressure. Measurements of radon gas content in air exhausted from mines have shown that the radon gas emitted into the atmosphere was 20% less with the air-blowing system than with an exhaust system [Franklin 1981]. This indicates that less radon gas diffused into the ventilated areas when an air-blowing system was utilized than when an exhaust system was used.

c. Exhaust Duct System (Pull System)

In the exhausting or pulling system, contaminated air is drawn from the working face by a duct that runs from the face to the main passageway in the primary air system through the access tunnel. Fresh air is then drawn into the access tunnel toward the work area by the pressure gradient created by removing air. Exhausting (pulling) air from the face instead of blowing (pushing) offers the following advantages:

- Fresh incoming air is maintained in the tunnel used by miners to access the active stope, and

- The contaminated air within 10 feet of the duct is very effectively removed from the work area

The major disadvantage of using the exhaust system is that only the area within 10 feet of the end of the exhaust duct is effectively ventilated [Rock et al. 1971]. Work areas further away may receive little air movement. Another disadvantage is that if the air must travel through the access tunnel and drifts that contain ore, then the air becomes contaminated as it is drawn toward the working area. Also, when air is drawn through ducts, the ducts are under negative pressure and thus must be reinforced or rigid to prevent collapsing. Finally the static pressure differential across an exhaust (pulling) system is greater than that across an equivalent blowing (pushing) system with comparable total pressure losses [Rock et al. 1971]. Because exhaust systems have higher static pressures, they are also more prone to leakage.

d. Push-Pull System

A push-pull system contains two ducts in the accessway, one for pushing clean air to the face and the other for exhausting air from the face back to the primary air system. This system has many of the advantages of both the push and the pull systems including the following:

- The blowing of air that sweeps across and ventilates the active face, thus providing good dilution in work areas;

- The efficient collection of contaminants near the work face; and

- Reducing the contamination of air in the access tunnel.

The main disadvantages are the cost and that it occupies more drift area [Rock et al. 1971].

5. Overpressurization and Mine Pumping

The amount of radon gas diffusing into mine spaces from interstitial rock is dependent on the pressure in the mine space. The lower the atmospheric pressure in the mine space as compared to the pressure in the interstitial rock, the more radon gas will pass from the rock to the mine space. Conversely, the greater the pressure in the mine space as compared to the rock, the less radon gas will seep into the mine space. Overpressurization and mine pumping are two control measures which take advantage of this principle to reduce concentrations of radon gas.

In overpressurization, more ventilation air is pushed into mine spaces than is removed. Although Edwards and Bates [1980] have stated "nothing that we have found provides mining companies with sufficient guidelines for applying the overpressurized ventilation system effectively," they conducted a mathematical study of overpressurization and drew the following conclusion: overpressurization does decrease the radon flux. It was estimated that a 2% pressure differential in a sandstone matrix would result in a 50% reduction in radon flux with mine sink lengths of 100 meters or less. A mine sink is an area either in the mine itself or a naturally occurring space or lattice in the matrix where the interstitial air can flow. If the distance between the sink and the mine space approaches 200 meters, the benefit of overpressurization is lost. Because of the dramatic increase in radon gas in the sink area during overpressurization of work areas, no miners should be allowed in those sinks without proper respiratory protection. However, many open spaces that can serve as sinks are filled in and cannot be occupied.

The Bureau of Mines is gathering information on the effects of overpressurization in mines. Data from the pressurization of an enclosed chamber in a mine indicated that the radon concentration was 99% lower than the concentration under static conditions and 92% lower than the concentration under controlled ventilation conditions [Bates and Franklin 1977]. In a study by Schroeder et al. [1966] of mine areas that were pressurized by 10 mm of mercury, the radon flux decreased from 5 to 20 fold as compared to normal ventilation conditions.

In mine pumping, a negative pressure is created in the mine space by sealing air intake openings and permitting the exhaust fans to operate. This is done during an offshift when no miners are in the mine. Because of the negative pressure created in the mine with respect to the surrounding rock, radon is drawn into the mine space from the interstitial rock at a rate higher than would occur under static conditions. The air intakes must be opened well before miners enter the mine to permit the ventilation system to remove the radon gas and radon progeny that have accumulated in the mine spaces. After this accumulation has been removed, the mine spaces should have lower concentrations of radon gas (and therefore radon progeny) when the miners reenter the mine. This is because much of the radon gas in the surrounding interstitial rock has been removed and is not available to diffuse into the mine working areas. However, monitoring of these areas would be required prior to allowing miners to enter. More studies are needed to determine the effectiveness of this control procedure [Bates and Franklin 1977].

6. Fan Operation

Continuous fan operation is essential in a mine for maintaining low radon concentrations during working hours. When the main exhaust ventilation system of 1 mine was shut off, radon gas concentrations increased 1,600% in 3 hours and even after 3 hours of fan operation, the radon gas concentrations failed to return to normal [Franklin et al. 1978]. In the first 5 minutes of a fan shutdown, 1 WL may be exceeded [Musulin et al. 1982]. For fan shutdowns of 15 minutes or more, underground miners should be evacuated to areas with natural downcast ventilation [Musulin et al. 1982]. It has been estimated that at least 2 hours of ventilation should be allowed for each hour of fan shutdown [Franklin et al. 1978]. Spare fans, fan maintenance, and backup electrical systems should be used to minimize shutdown.

C. Bulkheads

1. Description

The second most important control measure used in underground mines today is the construction of bulkheads across inactive stopes or drifts [Bates and Franklin 1977]. Bulkheads isolate inactive stopes, prevent the mixture of contaminated air from these stopes with fresh air, and help control the direction of air flow to working areas.

Maintaining a negative air pressure behind a bulkhead will prevent leaks [Franklin 1981]; this is important because radon progeny concentrations can exceed 1,000 WL behind a bulkhead [Bates and Franklin 1977]. In addition, bulkheads must be strong and flexible enough to maintain an airtight seal during typical mining conditions, such as the ground movement and air shocks from blasting and the impact from accidental contact with mining equipment.

A bulkhead consists of three functional parts: (1) the primary structure, (2) the seal between the primary structure and the rock, and (3) a surface seal on the rock within one meter from the plane of the bulkhead [Summers et al. 1982].

The primary bulkhead structure fills most of the opening in the stope and provides resistance to shocks from blasting or contact with machinery. The primary structure consists of timber or an expanded metal lath covered with a continuous non-porous membrane. The membrane may be attached to, or sprayed upon, the timber in the primary structure. The membrane must not crack or develop holes or leaks during mining activities [Franklin 1981; Summers et al. 1982].

The second part of the bulkhead, the seal between the primary structure and the surrounding rock, must resist running water and the air shocks and rock movements due to blasting.

The third part of the bulkhead, the seal on the surface of the rock within one meter from the plane of the bulkhead, must be made of a material that adheres to damp rock surfaces and can withstand mining activities. Summers et al. [1982] tested the efficacy of this procedure and found that the amount of radon gas escaping through the surrounding rock was insufficient to warrant the uniform use of a wall sealant, provided that all cracks, fissures, and holes were sealed to prevent major leaks.

2. Membrane Sealants Used on Bulkheads

Summers et al. [1982] evaluated 22 different materials for use as bulkhead sealants, looking at the flammability, health and safety hazards, strength, adhesion, flexibility, and radon gas permeability of each material [Summers et al. 1982]. The two best sealants for bulkheads were a preformed ethylene propylenediene monomeric rubber (EPDM) membrane and Aquafas 48-00®, a water-based mastic. A single sheet of the EPDM membrane was laminated (dry) between two layers of plywood; the Aquafas 48-00® was then troweled and sprayed onto a plywood surface. Summers et al. [1982] concluded that a material's permeability to radon gas was less important than its ability to prevent air leaks by its adhesive properties and resistance to tearing or brittle fracture. Steinhausler et al. [1981] recommended polyamide foil as the membrane component in a bulkhead because of its low radon permeability, high strength and flexibility, water resistance, and low cost.

3. Negative Air Pressure Behind a Bulkhead

A slight negative pressure behind the bulkhead of about 0.03 cm water with respect to active areas will prevent radon gas leaks into fresh ventilation air [Thomas et al. 1981]. To maintain the negative pressure, a bleeder pipe with a small fan is required to vent a bulkhead or series of bulkheads into the exhaust air [Franklin 1981].

A charcoal trap can efficiently adsorb radon from the bleeder pipe. During an experiment by Summers et al. [1982] a charcoal trap adsorbed 99.8% (calculated) of the high concentration of radon gas (34,249 pCi/l) behind a bulkhead; the activated charcoal worked well regardless of the temperature or humidity in the mine.

For a daily evacuation rate of 5%, the average age of air behind a bulkhead is 20 days. Because the half-life of radon gas is 3.8 days, radon gas has time to decay behind a bulkhead [Bloomster et al. 1984b].

4. Efficiency

Because mines differ in the air volume from the worked out areas that can be controlled by bulkheads, reports about the overall efficiency of bulkheads in controlling radon gas emissions vary. Based on experiments in two mines, Bloomster et al. [1984b] estimated that the use of the efficient bulkheads designed by Summers et al. [1982] and the use of carbon filters could reduce radon gas emissions into the atmosphere by 14-80%, depending on the percentage of the mine with bulkheads. When 40-45% of a mine was controlled by bulkheads, Thomas et al. [1981] estimated that traditional bulkheads reduced radon emissions by 30-52% from a test mine. Kown et al. [1980] used a hypothetical mine model to estimate that 100 bulkheads sealing 12.5 stopes would reduce the overall radon gas emissions into mine air by 2.25 Ci/day, a reduction of 25%.

In summary, bulkheads are very effective in reducing radon gas (and thus radon progeny) in mine air. Especially promising are the new bulkheads designed by Summers et al. [1982] and further tested by Bloomster et al. [1984b]. These bulkheads may eventually replace the leakier and more flammable polyurethane bulkheads presently being used underground.

D. Backfilling

In the uranium mining process, large quantities of ore are brought to the surface, leaving voids which may collapse if they are not stabilized. The tailings remaining after the uranium is extracted are often used as backfill. There are three benefits of backfilling stopes: (1) ground stabilization, (2) reducing the ventilation requirements by decreasing the mine volume taken up by air, and (3) allowing the removal of the ore in pillars [Franklin et al. 1982].

The process of backfilling involves three steps [Raghavayya and Khan 1973; Franklin 1981]. First, the coarser fraction of the tailings are separated out by hydrocyclones. Next, the coarse tailings "sand" is mixed with water to form a slurry and pumped into worked-out stopes. Sometimes the slurry is mixed with cement before pumping. After the water in the slurry percolates away, the stope is left filled with densely packed sand or cement.

The radon progeny hazard can be increased, at least temporarily, by backfilling. Although the sand has considerably less radium than the ore or host rock, the finely divided sand has a larger surface area and many fine interstices between the grains through which radon gas can move. Therefore, the radon gas emanation rate of the sand is much higher than the ore or host rock [Raghavayya and Khan 1973; Thompkins 1982]. During backfilling, agitation of the slurry releases high concentrations of radon gas [Bates and Franklin 1977]. Also, high concentrations of radon gas can collect above the sand in the newly filled stope (possibly reaching 65,000-75,000 pCi/l). Thus the advantage of decreasing the ventilation volume with the backfill must be weighed against the increased emanation rate of the backfill [Bates and Franklin 1977]. Mixing the slurry with cement will not prevent this increase in emanation rate because the radon gas can also travel freely through fine pores in the cement, especially water-filled pores. Indeed, radon gas emanates from porous cement, sand, or ore at a higher rate when it is wet than when it is dry unless the dry material is overlain with a thick layer of water [Thompkins 1982; Bates and Franklin 1977]. Wet, freshly cemented tailings emanate radon at a high rate that gradually decreases to a steady state as the cement dries [Thompkins 1982].

Although backfilling can produce transient increases in radon gas, it can also be efficacious in reducing overall radon progeny emissions from a mine [Bloomster et al. 1984b; Franklin 1981]. As currently practiced, backfilling can reduce the ventilation volume of a stope by 90% or more. During experiments in a mine, Franklin et al. [1981] found that backfilling 90% of a stope reduced the total radon progeny emissions from the stope by 85%. A feasibility study estimated that backfilling can be as effective as bulkheading in reducing overall radon progeny emissions; however, the cost is much higher [Bloomster et al. 1984b]. Two field studies [Franklin et al. 1982; Raghavayya and Khan 1973] reported extremely high emanation rates from cemented or sand backfill; however, in both instances the backfill was wet; these studies did not report the efficacy of the backfill after it dried.

Four methods may improve the efficacy of backfilling [Franklin et al. 1982; Bloomster et al. 1984b]: (1) covering the backfill with one meter of clean sand, (2) sealing the surface of the tailings, (3) using a bulkhead to seal the backfilled stope and maintaining a negative pressure behind the bulkhead, and (4) using nonradioactive materials as backfill instead of mill tailings.

In summary, backfilling with uranium tailings can be as effective as bulkheading in reducing radon progeny emissions, although it is more costly. Because high radon progeny concentrations are emitted from wet backfill and during the backfilling process, backfilling should not be used in active mine areas and miners should be protected from overexposure during backfilling operations.

E. Sealants Used on Mine Walls

This section describes sealants used as diffusion barriers against radon gas, including how the sealants are applied and the best materials used as sealants. Also, the effectiveness of sealants for reducing radon emanation and exposure will be discussed.

1. Description

a. Sealant Application Methods

Sealant application can involve four steps: (1) clearing the area, (2) applying an undercoating, (3) applying the sealant, and (4) applying an overcoating. First, the labor-intensive step in sealant application is clearing the area of loose rock to provide a smooth surface before applying the sealant [Lindsay et al. 1981a]. Shotcrete or Gunite is troweled into any large cracks in the surface [Franklin et al. 1977]. Second, an undercoating of shotcrete or Gunite is troweled or sprayed onto the prepared surface. The undercoating alone will not act as an effective barrier to radon gas, although it does provide a smooth supporting surface for the fragile sealant coating [Lindsay et al. 1981a; Franklin et al. 1977]. Third, a layer of sealant, usually an acrylic polymer, is sprayed or placed on the undercoating. The undercoating and sealant coating should be different colors to ensure complete coverage [Franklin 1981]. Fourth, an overcoating should be applied; the overcoating can be a second layer of sealant, another type of sealant, a layer of shotcrete, or some combination of these materials [Franklin 1981; Steinhausler et al. 1981]. An outer layer of shotcrete protects the sealant surface against mechanical damage in the mine.

b. Sealant Materials

The ideal sealant material should meet a variety of criteria to resist conditions within a mine [Franklin et al. 1975a; Steinhausler et al. 1981]. The sealant material should:

- Reduce the radon emission rate by 50% or more;
- Be easily applied (i.e., sprayable);
- Lack toxic vapor emissions during application or curing;
- Resist flame, fire, and water;
- Tolerate wide changes in temperature;
- Cure in a mining environment (40-60°F, 40-100% relative humidity);
- Possess mechanical strength and flexibility; and
- Lack electrical hazards (such as found with metal foils).

The sealants that performed well in a variety of laboratory and mine experiments [Franklin et al. 1975a, 1975b; Lindsay et al. 1981a, 1981b; Steinhausler et al. 1981; Summers et al. 1982] included:

- Hydro Epoxy 156®, a two-component, water-based epoxy;
- Hydro Epoxy 300®, a water-based epoxy;
- VMX-50 VML®, a water emulsion acrylic latex;
- VMX-50 BMT®, a water emulsion acrylic latex;
- Polyamide foil sheets;
- Ethylene propylenediene monomer (EPDM) rubber membrane 1.12 mm thick, often used as a roof sealant; and
- Aquafas 48-00®, a water-based mastic.

The estimated lifetime for sealants is approximately 5 to 7 years [Bloomster et al. 1984b]. In addition, the best use of sealants occurs in areas either with high radon emanation rates or where there is little chance of damage from mining activities; these include mined-out areas, lunchrooms, shops, intake airways, and inactive stopes [Kown et al. 1980; Franklin et al. 1980; Bloomster et al. 1984b].

Edwards and Bates [1980] of the Bureau of Mines developed a computer model to evaluate the effect of pinholes in an otherwise impermeable sealant. They concluded that pinholes (2 mm in diameter) were not a problem unless there were several thousand visible pinholes per square meter of sealant.

2. Effectiveness of Sealants in Reducing Radon Emanation Rates

The effectiveness of sealants depends, in part, upon the porosity of the rock walls. Sealants produce the greatest decrease in radon emanation when applied to sandstone or other porous rock; sealants applied to granite will appear to be less effective because granite provides a natural barrier to radon emanation [Lindsay et al. 1981a]. Thus results from the tests for the effectiveness of sealants vary greatly depending on the porosity of the rock walls along with the mine ventilation rate, the grade of the uranium ore, and other factors.

Five field experiments conducted by the Bureau of Mines between 1975 and 1981 showed that sealants (in this case, water-based epoxy and water-based acrylic latex) reduced radon gas emanation by 50-75% [Franklin 1981]. An acrylic latex sealant and a Gunite (dry-mix concrete) undercoating reduced the radon emanation by 75% when applied to sandstone [Lindsay et al. 1981a, 1981b]. Bloomster et al. [1984b] estimated that the overall decrease in radon emissions would be 56% if the same sealant coating was applied to 80% of the mine surfaces. Although sealants were less effective and more costly than bulkheads, the use of sealants is less disruptive to the mining process than the use of bulkheads [Bloomster et al. 1984b].

In summary, there are at least seven materials available that make effective mine sealants. These materials can reduce radon emanation from mine walls by 50-75%.

F. Controlling Radioactive Water Underground

Radium-, barium-, or radon-bearing waters cause radon control problems in underground mines. Radon-bearing water releases radon gas until the concentration in air reaches approximately three times the concentration in water [Thompkins 1982]. Open ditches, sumps, or other water accumulations near intake airways or active areas cause unnecessary contamination [Rock and Walker 1970].

Both iron mines in Sweden and coal mines in Poland use ventilation as the primary control for radon released from water. A coal mining company in Poland reduced radon concentrations in air by precipitating out the sulfate salts of barium and radium in the water [Tomza and Lebecka 1981]. A uranium company in Sweden proposes to drill boreholes around the mine and pump up the radon-bearing water into a nearby lake. This method is untested [Snihs 1981]. Thompkins [1982] suggests that placing a ring of wells around a uranium ore body, under a vacuum of 4 psi, and lowering the water table may reduce radon concentrations in a uranium mine by causing air and gas to flow to the wells.

G. Automation

Another radon progeny control method is increased automation. Techniques such as robotics that minimize the time the miner spends in the high exposure areas of the mine and in activities such as drilling, blasting, or loading ore, will decrease the miner's radiation exposure. Although, at present, robotics has a limited place in the mines, it may be possible in the future to further automate the ore mining process.

REFERENCES

ACGIH [1984]. Industrial ventilation--A manual of recommended practice. 18th edition. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Bates RC, Franklin JC [1977]. U.S. Bureau of Mines radiation control research. Proceedings of the Conference on Uranium Mining Technology, Reno NV, April 25-29.

Bloomster CH, Enderlin WI, Young JK, Dirks JA [1984a]. Cost survey for radon daughter control by ventilation and other control techniques. Volume I. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152932.

Bloomster CH, Jackson PO, Dirks JA, Reis JW [1984b]. Cost survey for radon daughter control by ventilation and other control techniques: radon emissions from underground uranium mines. Volume II. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152940.

Bossard FC, LeFever JJ, LeFever JB, Stout KS [1983]. A manual of mine ventilation design practices. Second edition. Butte, MT: Floyd C. Bossard and Associates, Inc.

Cooper WE [1981]. A comparison of radon-daughter exposures calculated for U.S. underground uranium miners based on MSHA and company records. In: Gomez M, ed. International Conference: Radiation Hazards in Mining, New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 292-295.

Edwards JC, Bates RC [1980]. Theoretical evaluation of radon emanation under a variety of conditions. Health Phys 39:263-274.

Ferdinand FW, Cleveland JE [1984]. Philosophies and practices in radiation monitoring and exposure calculations in modern uranium mines. Unpublished report submitted to the National Institute for Occupational Safety and Health by the Quivira Mining Company.

Franklin JC [1981]. Control of radiation hazards in underground uranium mines. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 441-446.

Franklin JC, Bates RC, Habberstad JL [1975a]. Polymeric sealants may provide effective barriers to radon gas in uranium mines. E/MJ, September 1975, pp. 116-118.

Franklin JC, Nuzum LT, Hill AL [1975b]. Polymeric materials for sealing radon gas into the walls of uranium mines. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8036.

Franklin JC, Meyer TO, Bates RC [1977]. Barriers for radon in uranium mines. U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8259.

Franklin JC, Meyer TO, McKibbin RW, Kerkering JC [1978]. A continuous radon survey in an active uranium mine. Mining Engineering, pp. 647-649.

Franklin JC, Musulin CS, Bates RC [1980]. Monitoring and control of radon hazards. Proceedings of the Second International Mine Ventilation Congress, Reno, NV, pp. 405-411.

Franklin JC, Weverstad KD, Black JW, Cleveland JE [1981]. Radiation hazards in backfilling with classified uranium mill tailings. Fifth Annual Cent. New Mexico AIME Uranium Seminar, Albuquerque, NM.

Franklin JC, Washington RA, Kerkering JC, Montone H, Regan R [1982]. Radiation emanation from stopes backfilled with cemented uranium mill tailings. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8664.

Kown BT, Van der Mast VC, Ludwig KL [1980]. Technical assessment of radon-222 control technology for underground uranium mines. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation Programs (ANR-458). Technical Note ORP/TAD-80-7, Contract No. 68-02-2616, Task No. 9.

Lindsay DB, Oberholtzer JE, Summers CH [1981a]. Sealant tests to control radon emanation in a uranium mine. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report No. 83836.

Lindsay DB, Schroeder GL, Summers CH [1981b]. Polymeric wall sealant test for radon control in a uranium mine. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 790-793.

Lundin FE, Wagoner JK, Archer VE [1971]. Radon daughter exposure and respiratory cancer: quantitative and temporal aspects. U.S. Department of Health, Education, and Welfare, Public Health Service, National Institute for Occupational Safety and Health, National Institute of Environmental Health Sciences, Joint Monograph No. 1.

Musulin CS, Franklin JC, Roberts FA [1982]. Effects of a fan shutdown on radon concentration in a positive pressure ventilated mine. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8738.

Ragavayya M, Khan AH [1973]. Radon emanation from uranium mill tailings used as backfill in mines. In: Stanley RE and Moghissi AA, eds. Noble Gases. Las Vegas, NV: U.S. Environmental Protection Agency, National Environmental Resource Center, Office of Research and Development, EPA 600/9-76-026, pp. 269-273.

Rock RL, Walker DK [1970]. Controlling employee exposure to alpha radiation in underground uranium mines. Volume 1. Washington, DC: U.S. Department of the Interior, Bureau of Mines.

Rock RL, Dalzell RW, Harris EJ [1971]. Controlling employee exposure to alpha radiation in underground uranium mines: appendixes for the use of radon-daughter control specialists. Volume 2. U.S. Department of the Interior, Bureau of Mines.

Schroeder GL, Evans RD, Kraner HW [1966]. Effect of applied pressure on the radon characteristics of an underground mine environment. AIME Transaction, p. 235.

Snihs JO [1981]. Radiation protection in Swedish mines: special problems. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 283-285.

Steinhausler F, Pohl-Ruling J, Pohl E [1981]. Control of radon daughter concentration in mine atmospheres with the use of radon diffusion barriers. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 127-130.

Summers CH, Lindsay DB, Lindstrom RS, Alder KL [1982]. Evaluation of bulkheads for radon control. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Minerals Health and Safety Technology, Minerals Research Contract Report No. 86396, pp. 8-12, 17-24, 52-55, 75-76.

Thomas VW, Musulin CS, Franklin JC [1981]. Bulkheading effects on radon release from the Twilight Uranium Mine. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratory, PNL-3693/UC-11.

Thompkins RW [1982]. Radiation in uranium mines: a manual of radon gas emission characteristics and techniques for estimating ventilating air requirements. Part 2. CIM Bulletin 75(846):62-67.

Tomza I, Lebecka J [1981]. Radium-bearing waters in coal mines: occurrence, methods of measurement and radiation hazard. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 945-948.