SESSION VII

URANIUM MINE AIR CLEANING

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CHAIRMAN: A. J. Breslin

CONTROL OF RADON DAUGHTERS IN U.S. UNDERGROUND URANIUM MINES
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THE USE OF VERMICULATE TO CONTROL DUST AND RADON DAUGHTERS IN UNDERGROUND URANIUM MINE AIR
R. A. Washington, W. Chi, R. Regan

REVIEW OF PROBLEMS AND TECHNIQUES FOR REMOVAL OF RADON AND RADON DAUGHTER PRODUCTS FROM MINE ATMOSPHERES
Aurel Goodwin

CHAIRMAN'S OPENING REMARKS:

This is the first time there has been a session on uranium mines at an Air Cleaning Conference. The reason for this relates to the evolution of atmospheric control in uranium mines during the last two decades and to recent regulatory changes.

When Duncan Holaday and his co-workers from the U.S. Public Health Service began their investigations in uranium mines some 20 years ago, they found a virtual absence of control of uranium mine atmospheres, with the exception of the marginal effects of natural draft ventilation. As a result of their warnings and recommendations, uranium mine operators began to install mechanical ventilation, and this brought about gradual reductions in radon and radon daughter concentrations. Much more urgent action toward improvement in control was precipitated by the onset of lung cancers among uranium miners, which was first brought to wide public attention by the Congressional hearings of 1967. Those hearings also prompted legislation which gave stringent enforcement powers to regulatory agencies, and so the mining industry was subjected to increasing pressures to improve atmospheric control.

As long as the maximum permissible concentration (MPC) remained at 1 working level, mechanical ventilation by itself, when properly used, was substantially effective for achieving control. Last year the MPC was cut to one-third of a working level. These more stringent control requirements, by a factor of 3, seem to represent a kind of barrier that many of the mine operators are finding very difficult to surmount with ventilation along. Consequently, they are looking into supplementary methods of control.

The ideal method of control is to prevent the emanation of radon from rock into the mine atmosphere. Toward that objective, experiments have been run with rock sealants, but none of these have yet been found to be fully effective. Other methods have been tried for removing radon from the mine atmosphere, but results have been uniformly unsatisfactory. However, the removal of radon daughters by more or less conventional air-cleaning techniques does offer considerable promise, and this is probably receiving as much or more attention at the present time than any other supplementary method of control. Over the last years, experiments with various kinds of air cleaners have been conducted only sporadically, but, now, mining companies are becoming more interested and the U.S. Bureau of Mines is supporting a diversified program of development which should bring tangible results fairly soon.

The small number of papers at this session reflects the low order of priority which this subject has received up to now, but I hope to see an upsurge of interest before the next Air Cleaning Conference. I doubt that the interest in air cleaning for uranium mines will ever compete with the fanatic attention that has been given to in-place filter testing and methyliodide, but radon is a noble gas and so uranium mines have a vague kind of kinship with reactors and fuel reprocessing plants.

In a sense, the current problems in the uranium mine industry are reminiscent of the problems that were faced and solved by the feed materials plants back in the late 40's and 50's, and I think that in many respects the technology is similar. Nonetheless, uranium mines present special challenges, and it isn't possible to transpose directly the technology from above ground to below ground. However, I do think that the collective expertise of this assembly can be of considerable benefit to the mining industry, and this is a suitable forum to discuss their current problems, and hopefully some solutions.

CONTROL OF RADON DAUGHTERS IN U.S. UNDERGROUND URANIUM MINES

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Abstract

Control of radon daughters in U.S. underground uranium mines is still primarily a problem of quickly affecting a thorough and efficient exhange of contaminated underground mine air with fresh surface air. As radiation standards have been made more stringent, and as mines have been developed deeper and their workings have become more extensive, radiation control by ventilation alone has become more difficult. As a consequence, both mechanical air filters and electrostatic precipitators are now being used on a moderate scale as a means of supplementing the radiation control effects achieved by conventional ventilation.

Introduction

Exposure of underground workers to alpha radiation through inhalation of airborne radon-daughter products* is a major problem in uranium mines. Epedemiological studies (1)** have shown such exposure to be associated with an increased occurrence of lung cancer.

Standards for maximum allowable cumulative exposure to radon daughters make it mandatory that an average atmospheric concentration no greater than 0.33 working level (W.L.) be maintained. This constitutes an average concentration of about 0.4 Mev of alpha energy per liter of air from the daughters RaA, RaB, and RaC in decaying through RaC^1.

In order to comply with current health standards, it is frequently necessary to affect a fresh air change in the mine workings every 5 to 10 minutes. This sometimes requires large enough air volumes to become prohibitively expensive or can introduce operating problems and create other health hazards. In these cases, the ability to control radiation by cleansing the air underground may offer a practical solution.

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* RaA(Po^{218}), RaB B(Pb^{214}), RaC(Bi^{214}), and RaC^1(Po^{214}), members of the U^{238} decay series.

** Numbers in parentheses refer to references at the end of this report.

Radon daughters are positively charged particulates, which readily attach to dust and other condensation nuclei; hence, they can quite easily be removed from mine air by either filtration or electrostatic precipitation. A discouraging factor, however, is that radon daughters regrow rapidly into the cleansed air that is still contaminated with radon gas.

Where a commonly found concentration of 300 pCi of radon gas per liter of air is present, only 5 minutes is required for 0.33 W.L. of daughters to develop. This is the main reason that air-cleaning devices are not more widely used as a means of providing radon-daughter control.

Control By Conventional Ventilation

Although mechanical ventilation is an effective means of protecting underground workers from the radon-daughter hazard, ventilation requires careful planning and diligent maintenance to sustain its effectiveness (2). The complicating factor in controlling radon daughters is that for a given contamination burden, the degree of the hazard increases with time. Therefore, not only must radon and its daughters be removed quickly from production areas, but they also must be removed quickly from other occupied mine areas such as haulageways. Generally, the more extensive the underground workings, the more difficult control becomes.

The ideal ventilation system introduces uncontaminated air directly into each mining area and exhausts contaminated air through unoccupied return airways. Such a system offers the advantages of lower overall air volume requirements and generally lower pressure requirements.

The difficulty in providing an ideal system of ventilation for uranium mines frequently involves economics. Uranium mine intake airways should be driven in waste rock. Consequently, an unacceptably high initial investment may be necessary to provide the classic split or parallel ventilation system so often applied in coal and potash mines.

In most uranium mines, large areas are ventilated using a series ventilation system in which air from one active section is used to ventilate the next section. The air volume required through all mine workings in each series circuit is dictated by the air quantity required to provide radon-daughter control in workings near the circuit's terminus. It is in these workings, near the end of series circuits, where air-cleaning devices have most frequently been applied in an attempt to provide an expedient method of radiation control without adding more primary ventilation.

Removal of Radon Daughters by Filtration(3)

Air filters are most often installed on the intake side of secondary fans blowing air into working places through tubing. Filter holders vary in configuration according to space limitations and filter surface-area requirements. Generally, four to eight 2- by 2-foot-square pleated paper-fiberglass filters, 1-foot thick, are arranged to cover the fan inlet. Prefilters (fiberglass furnace filters) capable of removing particulates 10 microns and above are generally used to prolong the life of final filters.

Volumes of air filtered do not generally exceed 3,000 to 5,000 cfm. Air in the range of 1-2 W.L. is filtered to less than 0.1 W.L. Most final filters are advertised as being better than 95 percent efficient in removing particles 0.3 microns in size.

Fans commonly used are 5 hp., axial-flow type, rated at 5,000 cfm. unrestricted flow. Using clean filters, about 1/2-inch water gage pressure is required to pass 2,500 cfm through the filters. Filter life depends on moisture and dust content of the air. About 2 months is the average life of the filters, which are changed only when they will no longer pass sufficient air.

Final filters are relatively expensive (in the range of $100 each), therefore, a method of cleaning them for reuse is desirable. Some experimentation in cleaning the filters has been accomplished but with unsatisfactory results.

Problems encountered with mine air filtration are excessive dust loading, moisture affecting the filter media, and high filter costs. Some of the filter media collapses when it is exposed to high moisture conditions allowing air leakage around and through the filter.

Electrostatic Precipitation of Radon Daughters

A few uranium mining companies have installed standard industrial-type electrostatic precipitators underground to improve the air quality provided by primary ventilation. There is nothing particularly unique in the design of these units, except that their power supply systems are sometimes provided with added insulation to withstand high humidity and the other abusive conditions found in an underground environment.

Precipitator modules are erected across the mine drift through which the air to be cleaned is passing. Voltage adjustments are then made to satisfy airflow conditions and dust collection efficiency.

The most interesting aspect of electrostatic precipitation is that it appears that a bonus in air benefication is achieved by removal of condensation nuclei from mine air. Apparently the electrically charged radon daughters growing into the cleansed radon-gas laden air have a greater tendency to adhere to mine surfaces than is the case where air is merely filtered. Preliminary tests comparing projected growth concentrations of radon daughters (based on elapsed time after cleansing and amounts of radon gas present) with actual measured atmospheric concentrations have indicated that this beneficiation may be greater than 25 percent. Of course, as the air traverses through the mine and picks up more condensation nuclei, the daughters will attach themselves to these particles and loose some of their affinity for mine surfaces. More studies of this air-cleansing phenomenon, commonly called radon-daughter "plate out", are being undertaken.

A distinct advantage of electrostatic precipitators over filtration units is that greater volumes of air can be cleansed more economically. Precipitator units can be moved from location to location, while filter media must be considered expendable.

Radon Gas Removal

The ultimate in radon-daughter control would be a system to cleanse air of radon gas, the precursor of the harmful daughter products. At the present, there is no practical way of doing this, although the operation can be performed in the laboratory in several ways.

Although radon is a noble gas, it can be made to unite chemically with certain fluorine compounds. These compounds are toxic, expensive, and degenerate rapidly when they contact moisture. Some experimentation with a cryogenic separation of radon from mine air has been accomplished. It is possible to make the separation, but the economics are highly suspect.

One of the more interesting recent proposals for removing radon from mine air is by centrifuging.

Considering all the radon-removal proposals which have been advanced, an adsorption process seems to be the most popular approach. Using the adsorption or solution process, the radon-contaminated mine air must be brought into intimate contact with the adsorbing or dissolving material. Radon is about 15 to 20 times as soluble in fats and oils as it is in water. Raschig rings were coated with tri cresyl phosphate, and mine air was circulated through the rings during one experiment. Radon was reportedly removed to a significant degree during this experiment, but the scale of the tests was so small that little was resolved regarding the practicality of the process.

The Bureau of Mines performed some field tests using a spiral-type industrial air cleaner filled with mineral oil rather than the water which it was designed to use. As the radon-contaminated mine air was drawn through the air cleaner, a thin layer of mineral oil circulated around the periphery of the spiral. The oil reservoir was only about 60 gallons, and the air capacity of the device was about 1,000 cfm. It was found that the oil quickly became saturated with radon. Attempts to rejuvenate the solubility potential of the oil by passing it through beds of silica gel were unsuccessful on the scale that was attempted. From data collected during the test, it appeared that about 250 gallons of radon-free oil would have to be intimately mixed with the mine air to achieve acceptable radon cleansing effectiveness. The impracticality of providing a 1 to 4 solvent-to-air ratio is obvious. The device required considerable space and a 10-hp. fan to move only 1,000 cfm.

In spite of these discouraging facts, the Bureau of Mines is currently supporting contract research work involved with methods of removing radon gas from mine air.

Conclusion

Development of improved methods for cleansing mine air of radon daughters and hopefully the development of a practical radon gas removal system will be a great benefit to underground uranium miners. Air-cleaning technology for uranium mines is currently in its infancy, and all experimentation in this regard is based on previous industrial experience utilizing air-cleaning equipment. Until air-cleaning technology has been advanced considerably beyond its present state, health protection for uranium miners will depend primarily on the application of well designed and diligently maintained conventional ventilation systems.

References

1. Lundin, Frank E. Jr., M.D., Dr. Joseph K. Wagoner, P.H., Victor E. Archer, M.D.; Radon Daughter Exposure and Respiratory Cancer Quantitative and Temporal Aspects, Joint Monograph No. 1, Public Health Service, 1971, 175 pp.

2. Rock, Robert L., R.W. Dalzell, and E.J. Harris; Volume 2, Controlling Employee Exposure to Alpha Radiation in Underground Uranium Mines, BuMines Handbook, 1971, 180 pp.

3. Rock, Robert L. and Donald K. Walker; Volume 1, Controlling Employee Exposure to Alpha Radiation in Underground Uranium Mines, BuMines Handbook, 1970, 72 pp.

DISCUSSION

THOMAS, J: You talked about economics. Suppose you had a system for taking out radon that could handle about 2500 cfm and might last a year or so. What would be the maximum cost of such a system to be economically feasible in uranium mine applications?

ROCK: This is a difficult question. The parameters have to be described carefully. Right now, ventilation costs in the average uranium mine are in the neighborhood of 50 cents to $2.00 per ton of ore. I would need more detailed criteria to answer your question. Of course, the grade of the ore, the radon emanation rate, current ventilation problems, and other variables are critical factors.

FIRST: I understood you to say that the nuclei penetrating the electrostatic precipitator migrate to the walls of the tunnels. Did anyone ever reverse the polarity of the electrostatic precipitators to see if the walls would repel the nuclei? I ask this question because the collection mechanism is not clear; first, the electrostatic precipitator is a unipolar charging device, and second, the humidity in the mines is inimicable to electrostatic effects.

ROCK: In this case, the main interest was in collecting as many of the nuclei as possible, but I don't think the polarity was ever reversed. The nuclei were positively charged.

THE USE OF VERMICULITE TO CONTROL DUST AND RADON DAUGHTERS IN UNDERGROUND URANIUM MINE AIR

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Abstract

In uranium mines, the purification of underground mine air can be accomplished by the removal of dust particles and radon daughters using filters.

Full-scale statistically designed experiments with flow rates up to 10,000 cfm have been conducted at Denison Mines Ltd. on mine air filtration with Vermiculite as filter material. Various filtration bed thicknesses were chosen with different face velocities through each bed thickness. Results on total dust, respirable dust and radon daughters collection efficiencies were analysed statistically. It is shown that these collection efficiencies are directly related to the filtration bed thickness. However, the different face velocities seem to affect only the collection of radon daughters. Optimum collection efficiencies for a clean bed of about 30% were found for respirable dust and radon daughters, and about 40% for total dust, using an 8-in. thick bed and a face velocity of 500 fpm. Dust build-up on the filter bed during operation led to an increase in collection efficiency, reaching 40% to 60% after two weeks.

Introduction

Contaminants in the underground uranium mine environment include diesel exhaust fumes, mineral dusts and radioactive materials (e.g. radon daughters). Excessive concentrations of these aerosols, inhaled over an extended period of years, may produce pneumoconiosis and lung cancer. The common practices for controlling these airborne contaminants are: (1) the sealing of worked-out areas to prevent diffusion of radon into ventilating air; (2) the circulation of large volumes of fresh air from surface to dilute these contaminants to a permissible concentration.

The sealing of worked-out areas can be easily and effectively accomplished but the contaminants introduced from the working stopes may raise the concentrations in the airways despite a good ventilation system and use of the maximum available amount of fresh air to dilute and disperse the contaminants.

Vitiated air could be filtered to reduce the dust and radon daughters to acceptable levels, and re-used prior to final discharge. This would be particularly advantageous in the winter when the incoming fresh air must be heated to a comfortable temperature. At the time of the experiment about 500,000 cfm of air was used for ventilation by Denison Mine. Since that time the flow has been increased to 650,000 cfm in order to improve the air quality further. Filtration and recirculation could decrease the air volumes required in certain areas of the mine and thereby avoid an overall increase in the mine airflow. Thus, an economically and technically feasible filter could improve the underground mine environment and reduce the overall costs of ventilating the mines.

Tests of commercial filters in an underground uranium mine have indicated that removal of >99% of dust and radon daughters in the ventilating air is technically possible. However, in order to achieve this efficiency a very expensive filter is required (1), and these high efficiency filters tend to clog up rapidly, and must be replaced frequently. Moreover, at high relative humidities some filter media are weakened by absorbing moisture and rupture readily under the high pressure drops associated with high air:cloth ratios*.

In order to test an inexpensive filter medium which could be applied practically underground, a co-operative project between Denison Mines and Mining Research Centre has been performed using vermiculite as the filter medium because of its low cost, low density, and ability to withstand high humidity.

Experimental

Location of Test Site

The test site was situated underground at Denison Mine Ltd. in stope 10087 just south of Panel 8. Figure 1 shows the position of the test site relative to the intake and exhaust air shafts. Figure 2 is a more detailed plan of the test site. This location was chosen because the dust and radon daughter concentrations were high enough to permit observation of any significant effect due to filtration.

The experimental measurements taken at the test site, indicated considerable variations in radon daughter working levels** and concentrations of respirable and total dusts from day to day and hour to hour.

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*Air:cloth ratio is flow rate (cfm/ft^2 of filter surface area); it is also the true face velocity (ft/min).

**1.0 working level (W.L.) is the amount of radon daughters, in any proportion, which upon complete radioactive disintegration to Pb^{210}, emits alpha particles with a total energy of 1.3 x 10^5 MeV (8).

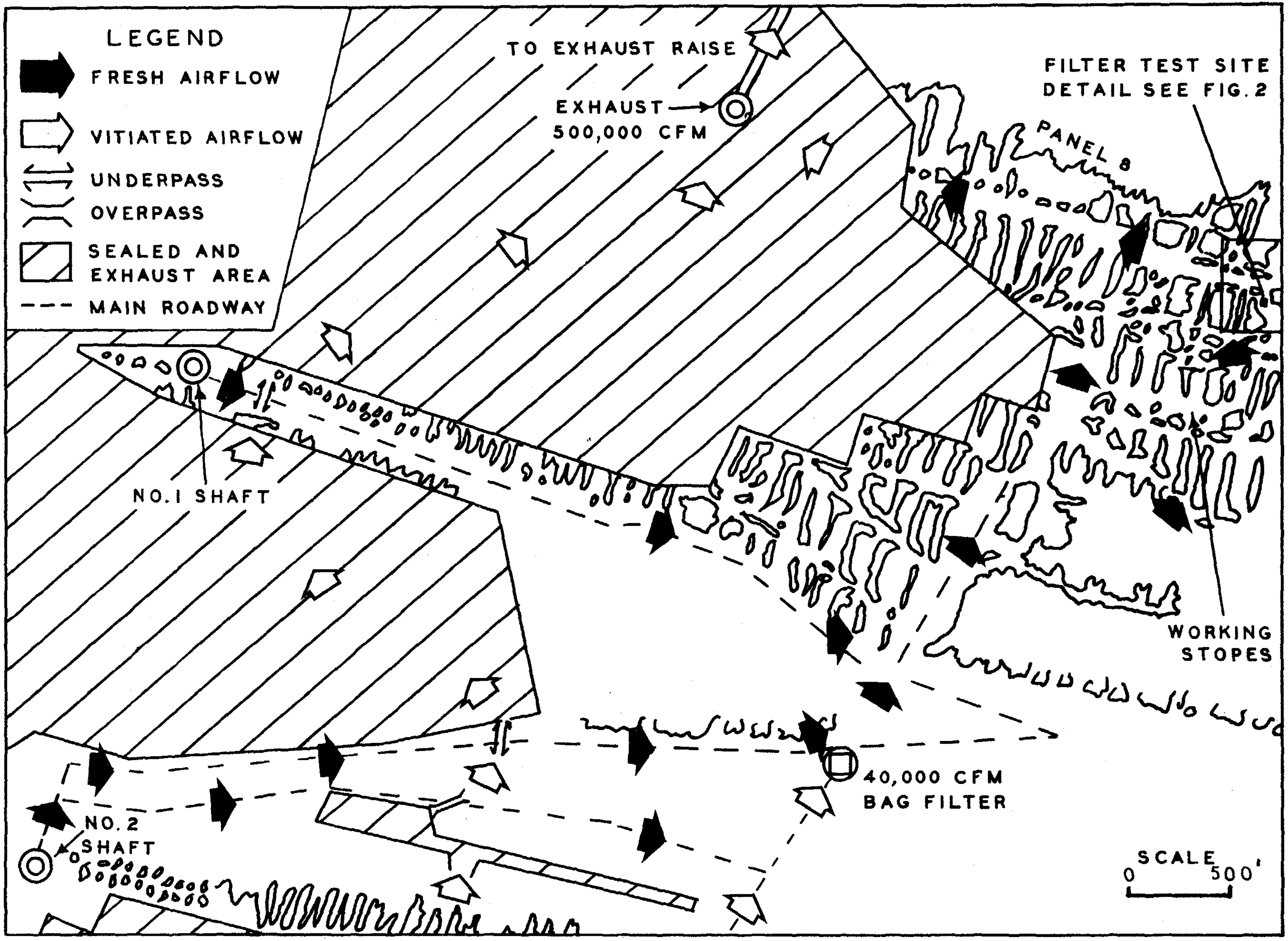

FIG. 1 LOCATION OF FILTER TEST SITE

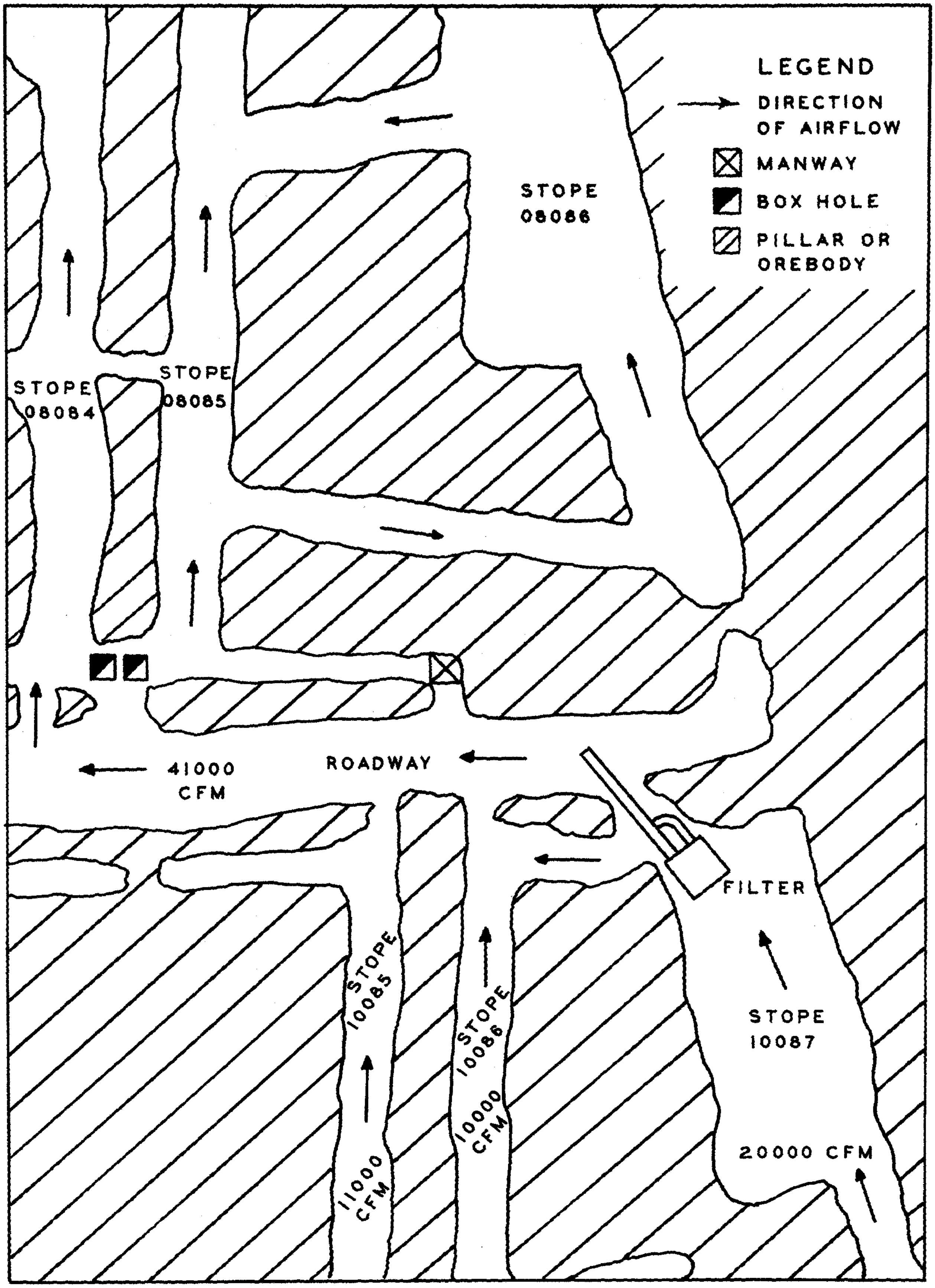

FIG. 2 DETAIL OF TEST SITE

Assuming the quartz content of the dust to be 50% to 70% (7), the suggested TLV for respirable dust is 0.1 to 0.2 mg/m^3 and that for total dust is 0.4 to 0.6 mg/m^3 (6). The TLV for radon daughters is 1.0 W.L. (4, 8). If the observed dust and radon daughters are close to the recommended TLV's, filtration of the air and reduction of the concentrations by 30 to 50% would permit ventilation of additional working areas before the air is finally exhausted.

The temperature at the test site was quite stable (54.5°F ± 0.5°F), and the very high relative humidity (98 to 100%) produced constantly foggy conditions which are typical of those in the general mine areas during the summer.

If the filter medium under test could meet the above efficiency requirements and if it remained unaffected by the high relative humidity, it would be considered satisfactory.

The filter box was located in the stope but, because of the rough terrain in the stope, most of the measuring instruments were set up in the roadway (Figure 2) near the outlet of the duct.

Description of Filter Test Apparatus

The objective of the experiment was to determine the effect of different bed thicknesses and different face velocities on the collection efficiencies for respirable and total dusts and radon daughters, using vermiculite as the filter medium. Three bed thickness of 2 in., 4 in. and 8 in. were chosen with four different face velocities of approximately 500, 320, 200 and 130 ft/min through each bed thickness.

In order to make the tests as realistic as possible, a full-scale filter test apparatus (Figure 3, 4) was designed and built. It was composed of a plenum 8 ft x 8 ft x 4 ft, with four 4 x 4 x 1-ft filter medium support boxes placed on the top. Vermiculite was spread to the desired thickness in the boxes which had a fine nylon screen and heavy, expanded wire mesh installed in the bottom to support the vermiculite and withstand dampness and high pressure drops across the filtration bed.

The total surface area of the plenum was 64 ft^2 but the effective area of the four retainers is approximately 50 ft^2. The air was drawn through the vermiculite by a 24-in. axial flow fan placed near the bottom on a sidewall of the plenum, and connected to 20-in.-diameter duct.

Since the axial fan with guide vanes has an A.C. and three phase motor, the volume flow (i.e. face velocity) could not be controlled by adjusting the speed of rotation of the blades using a potentiometer. Instead, the face velocity was controlled by means of an air flow control gate and by blocking off one, two, or three of the filter boxes to produce the desired face velocity through the remaining boxes.

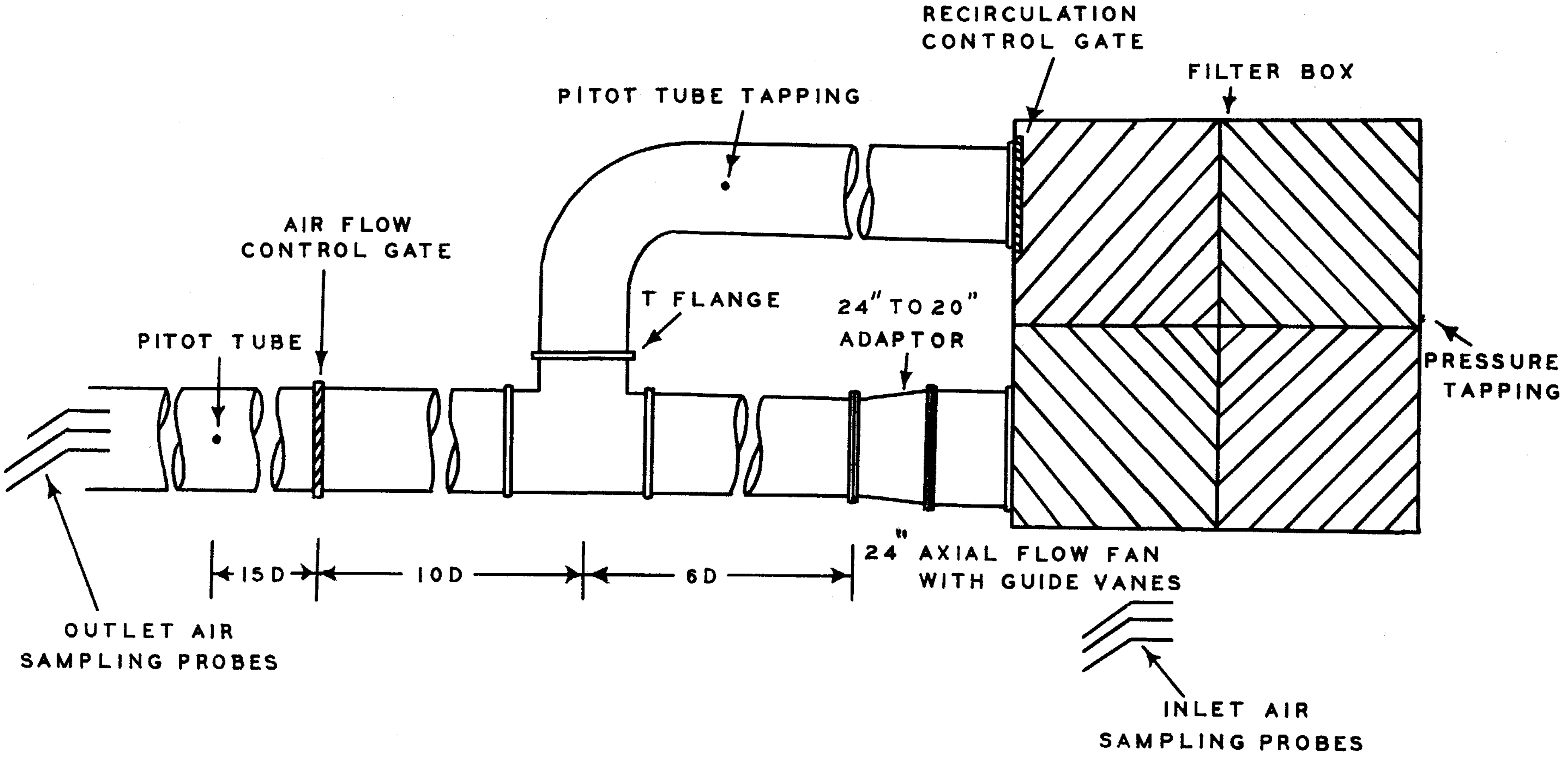

FIG. 3 TOP VIEW OF FILTER TEST LAYOUT

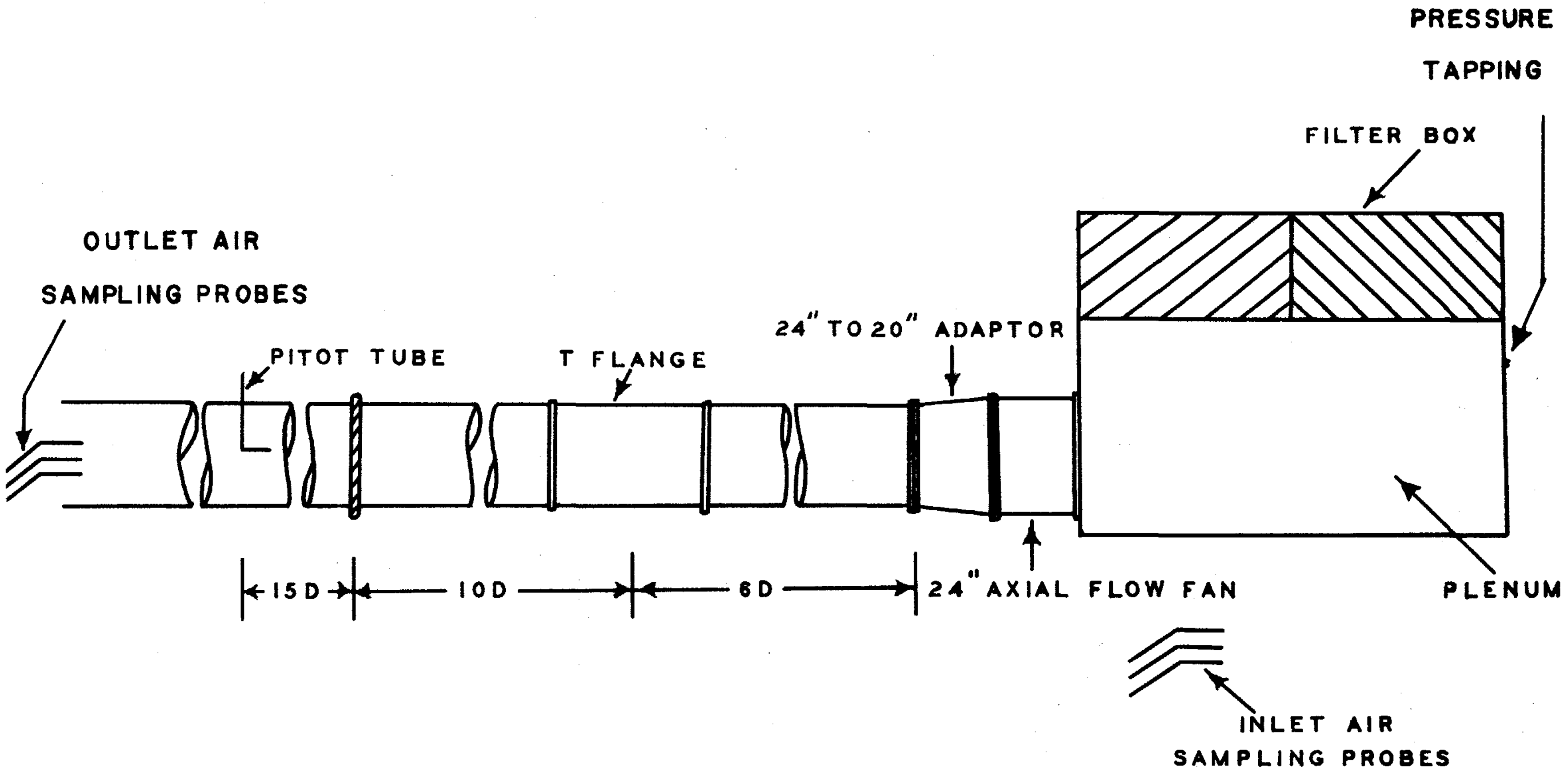

FIG. 4 SIDE VIEW OF FILTER TEST LAYOUT

In attempting to obtain the lowest face velocity (130 ft/min) by adjusting the air flow control gate, with none of the filter boxes blocked, the fan was found to be dangerously close to stalling. Therefore it was necessary to install the recirculation duct and gate which allowed part of the filtered air in the plenum to be recirculated. This increased the air flow through the fan and prevented stalling. Weather stripping was placed between the filter boxes and the plenum which effectively stopped any air leakage. Any other possible leakages between joints were sealed by caulking.

The possibility was considered that an error might have been introduced into the observed filter efficiency for radon daughters when partial recirculation was being used, because of regrowth of radon daughters in the recirculating portion of the air. A detailed analysis of this possibility was not undertaken because it was quite apparent that the solution of the differential equations and performance of the complex computations would take too much time; therefore some simplifying estimates were made, care being taken that the real situation would always be more favourable (i.e. would have a smaller error) than the estimated situation. The results indicated that the maximum error would be of the order of 5% (see appendix A for details of the estimate). Because the error in the efficiency measurements was estimated to be of the same order, it was assumed that the error due to regrowth of radon daughters could be neglected.

Experimental Design

This experiment was designed to permit statistical analysis of the results (2). Bed thickness and face velocity were the two independent factors selected to be varied; three fixed, quantitative levels were chosen for bed thickness, and four fixed quantitative levels were chosen for face velocities. The dependent variables were the total dust, respirable dust and radon daughters collection efficiencies. Considering all the probable experimental errors, and the accuracy with which the efficiencies could be estimated, the significant level was chosen as ten per cent.

For each bed thickness, four different face velocities were run to constitute one block. Since it was only possible to run one complete block on one day, a second block on another day, and so on, the experiment was a randomized block design with each day as a block and complete randomization within each block. The four face velocities and three thicknesses constituted twelve treatment combinations, and three replicates were taken for each treatment combination, for a total of thirty-six experimental runs.

The experimentation order of face velocities within each block was randomized by tossing two coins, a dime and a nickel. The four combinations of heads and tails represented the four different face velocities. Thus, if the first set of tosses came HH a face velocity represented by that combination is run first. If the same combination is repeated before the order is determined, this repeated combination is ignored. In adjusting the face velocity in the experiments the filter boxes were blocked off at random to minimize the effect of any unevenness of vermiculite bed thickness. Randomization of the order of experimentation in this way tends to eliminate the effect of any uncontrolled or time-dependent variables which were not considered in the design.

The mathematical model for this experimental design can be represented by:

$$X_{ijk} = \mu + T_i + V_j + TV_{ij} + \epsilon_{k(ij)}$$

where:

X_{ijk} represents the measured variable (collection efficiency); k represents the replicate (= 1, 2, 3)

μ is the true mean of all efficiencies (the true mean of the total population from which the samples were taken which gave the observed data)

T_i represents the bed thickness effect where i = 1, 2, 3

V_j represents the face velocity effect where j = 1, 2, 3, 4

TV_{ij} represents the interaction effect between T and V

$\epsilon_{k(ij)}$ represents the random error within the cell i, j where k = 1, 2, 3.

Experimental Procedures

Efficiencies of filters are frequently found to increase gradually as the filter loads up. In order to eliminate this effect, which would introduce an uncontrolled variable into the statistical analysis, the clean vermiculite was spread in the filter boxes to the prescribed thickness and allowed to run for a twenty-four hour period before taking readings. This procedure also tended to remove any very small vermiculite particles which might otherwise be collected at the downstream sampling probes and produce an erroneous efficiency measurement. At the end of the twenty-four hour period, the experiments were performed in the pre-determined order as described in "Experimental Design". One complete block was run on one day, and the fan was then shut off until the next day when another block was run.

Three sampling probes were placed inside the stope near the filter box, to observe the concentrations of total dust, respirable dust and radon daughters in the unfiltered air. Three sampling probes were also placed inside the 20-in. ducting at the exhaust end with interchangeable tips of suitable internal diameters in the probes to obtain approximately isokinetic sampling (9) for total and respirable dusts and for radon daughters in the filtered air.

The air samples were drawn through the sample probes by a vacuum pump. Sampling rates were predetermined and controlled by the use of critical orifices. Total dust and respirable dust were measured by collection on glass fibre filters and weighing as described previously (1). Respirable dust was obtained by using horizontal elutriators. Sampling times were limited to twenty minutes because in some cases the filter started to clog and the flow rate began to drop for longer sampling periods.

Radon daughters were collected on membrane filters. Two samples of 3 minutes each were taken during each 20 minute run, with a 10 minute interval between the samples.

The radon daughters concentration of each sample (in working levels) was measured using a calibrated HASL alpha survey meter* by means of the Kusnetz technique (3, 4). Dust concentrations by particle count in the filtered and unfiltered air were also taken using a Gathercole Konimeter. The relative humidity of the air entering and leaving the filter were taken using a wet and dry bulb psychrometer. A U-tube manometer was used to measure the pressure drop (expressed in inches of water) across the filtration bed. A pitot tube and inclined manometer were used to measure the air velocity in the duct, which gave the volume flow rate through the filter medium.

Results and Conclusions

The experimental data are summarized in Tables I, II and III. The efficiencies are shown in percentages. The variation between replicates within a treatment combination is quite widespread in some cases, as a result of the many experimental difficulties encountered in the procedure. In particular, the difficulty of weighing 1-mg dust samples accurately and precisely on filter discs weighting approximately 150 mg was rather formidable in view of the fact that the sample filter tare weight may vary as much as 0.2 mg during collection of the sample. A much longer sampling period

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*The design for the HASL meter was kindly supplied by Mr. A.J. Breslin, Director of the Health Protection Engineering Division of the USAEC Health and Safety Laboratory, New York. The unit was constructed by the Electronic section of the Elliot Lake Laboratory under the supervision of Mr. H. Montone and Mr. L. Tirrul.

TABLE I: Collection Efficiencies (%) of Vermiculite for Respirable Dust

Thickness	2-inch			4-inch			8-inch			
	Replicate			Replicate			Replicate			
F.V.	I	II	III	I	II	III	I	II	III	Average
500	22	19	27	28	35	25	44	48	40	32
320	21	15	38	30	11	32	24	36	38	27
200	35	15	21	30	38	27	28	19	37	28
130	17	14	17	12	14	14	23	26	20	17
Average		22			25			32		

TABLE II: Collection Efficiencies (%) of Vermiculite for Total Dust

Thickness	2-inch			4-inch			8-inch			
	Replicate			Replicate			Replicate			
F.V.	I	II	III	I	II	III	I	II	III	Average
500	47	20	33	38	44	26	55	61	39	40
320	28	32	33	44	50	46	63	42	47	43
200	35	35	37	34	50	30	48	31	36	37
130	43	27	28	18	23	0	31	31	31	26
Average		33			34			43		

TABLE III: Collection Efficiencies (%) of Vermiculite for Radon Daughters

Thickness	2-inch			4-inch			8-inch			
	Replicate			Replicate			Replicate			
F.V.	I	II	III	I	II	III	I	II	III	Average
500	19	16	39	28	34	29	39	33	33	30
320	25	17	33	16	27	26	36	28	29	26
200	13	21	22	27	24	21	27	24	26	23
130	22	11	16	18	25	15	17	13	16	17
Average		21			24			27		

should reduce the error, but this was not possible in the present study. The weights of the dust samples collected were too small to allow a distinction to be made between collection efficiencies of organic and inorganic dusts*.

In considering the data, the average efficiency for 130 ft/min face velocity seems to deviate from the average efficiencies for the other three face velocities in respirable and total dust collections. When two-way analyses of variance (ANOVA's) were performed for total and respirable dusts, using the data shown in Tables I and II, the F test(2) showed that variations in the face velocities have a significant effect on collection efficiencies, with a 99% confidence level. However, it is suspected that this effect may be spurious, since the opening of the recirculation gate to obtain a face velocity of 130 ft/min caused turbulence in the plenum which permitted a small amount of fine Vermiculite to be drawn off the bed, and mixed in the filtered air. This may have affected the collection efficiencies. This skepticism is further supported by one measurement taken on the four inch bed with the recirculation gate open; the weight of dust collected in the filtered air was greater than the weight collected in the unfiltered air. The efficiency for this case was taken as zero. However, even if fine Vermiculite blows out of the bed, it should not affect the radon daughter readings. A two-way ANOVA for the filter efficiencies for radon daughters is shown in Table IV, based on the data of Table III.

TABLE IV: ANOVA for Radon Daughters
4 x 3 with 3 Observations per Treatment Combination

Source of Variation	Deg. of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	Factor F
V_j	3	827.4	275.8	8.49
T_i	2	187.4	93.7	2.88
TV_{ij}	6	183.5	30.6	0.94
$\epsilon_{k(ij)}$	24	780.7	32.5	
Total	35	1979.0		

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*Preliminary tests, in which the dust samples were ignited, showed the fraction of mineral dust in the samples to be negligibly small.

Comparing the F values in Table IV with the critical values (2) it is apparent that the hypotheses $V_j = 0$ and $T_i = 0$ are rejected and the hypothesis $TV_{ij} = 0$ is accepted, for the preset 10% significance level. In other words, the face velocity has a significant effect on the filter efficiency for radon daughters, at a confidence level of > 99%. Similarly, the bed thickness has a significant effect, at a confidence level of > 90%. However, there is no significant interaction effect.

Neglecting the measurements taken at 130 ft/min face velocity, another two-way ANOVA was performed with the results shown in Table V.

TABLE V: ANOVA for Respirable Dust, Total Dust and Radon Daughters: 3 x 3 with 3 Observations per Treatment Combination

		Resp. Dust			Total Dust			Radon Daughters		
Source	df	SS	MS	F	SS	MS	F	SS	MS	F
V_j	2	122.9	61.4	0.90	133.8	66.9	0.83	234.7	117.3	3.16
T_i	2	571.0	285.4	4.20	826.9	413.5	5.15	277.0	138.5	3.73
TV_{ij}	4	373.4	93.4	1.38	422.7	105.6	1.32	67.9	16.9	0.45
$\epsilon_{k(ij)}$	18	1222.7	67.9		1444.0	80.2		688.7	37.1	
Total	26	2290.0			2827.4			1248.3		

From these calculations it can be seen that variations of face velocity do not have a significant effect on the collection efficiencies of respirable dust and total dust; i.e., the postulate $V_j = 0$ is accepted. However, the postulate is rejected for radon daughters; variations of face velocity have a significant effect on the efficiency, at a confidence level > 95%. Variations in bed thickness have a significant effect on efficiency, at a confidence level > 95%, for all three factors (total dust, respirable dust, and radon daughters). The interaction* effects are insignificant (at the preset level of 10%) in all three cases, i.e., the postulate $TV_{ij} = 0$ is accepted.

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* An interaction between two factors means that the change in response between levels of one factor is not the same for all levels of the other factor.

Although the ANOVA's indicate those factors which have a significant effect, no evidence can be obtained to indicate the optimum level of each factor. Therefore, in order to determine bed thickness and face velocity required for optimum collection efficiency, Students' t test (8) was applied to the means for each factor in Tables I, II and III. The results are summarized in Table VI. The data for a face velocity of 130 fpm were included in the calculations.

It is quite apparent that the major effect of changes in face velocity occurs between 130 fpm and 200 fpm. Further increases of face velocity, up to 500 fpm, have no statistically significant effect on the collection efficiencies for respirable and total dust. For radon daughters there is a statistically significant increase in collection efficiency in raising the face velocity from 200 fpm to 500 fpm, implying that the very small particles (0.2 to 0.5-μ diameter) to which the radon daughters are chiefly attached (10, 11) require a higher air velocity to enable them to impinge on, and adhere to, the vermiculite granules. Larger particles, in the respirable size range and above, reach their critical momentum (mv) for impingement at a lower velocity (between 130 fpm and 200 fpm), and any further increase of velocity has no effect*. These arguments are generally valid whether or not the results for respirable and total dust at a face velocity of 130 fpm are spurious, as suggested earlier (see p 13). If the 130 fpm results are erroneous, the only modification to the argument will be that the critical velocity for impingement of respirable (and larger) dust particles will be lower than predicted. In any case, there is little likelihood that a low face velocity would be used in a practical application unless it could be expected to give an appreciable gain in dust collection efficiency, as the ventilation engineer will probably be interested in passing the maximum possible volume of air through the smallest possible cross-sectional area of bed.

It is worthwhile to note the close relationship between the average collection efficiencies for respirable dust and for radon daughters, for corresponding conditions of bed thickness and face velocity, and the dissimilarity of the average efficiencies for total dust under the same conditions. This constitutes at least indirect confirmation of the suggested attachment of radon daughters primarily to respirable-sized dust.

The calculated t-values in Table VI for bed thickness indicate that the 8-in. bed is significantly more efficient than the 2-in. bed for collection of respirable and total dust, and radon daughters, at a confidence level of 90% or greater. However, the 8-in. bed does not appear to be significantly more efficient than the 4-in. bed, except for respirable dust, and the 4-in. bed does not appear to be

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*These conclusions are in quite reasonable agreement with predictions based on the aerodynamic behaviour of airborne particles.

TABLE VI: "Students' t" Test on Means

Face Velocities

Table Values (df = 16)

Probability *:	0.50	0.40	0.30	0.20	0.10	0.05	0.02	0.01	0.001
Students' t :	0.69	0.86	1.07	1.34	1.75	2.12	2.58	2.92	4.02

Comparison	t (Calc.)		
	Resp.	Total	Radon Daughters
500 vs 320 fpm	1.05	0.53	1.15
500 vs 200 fpm	0.92	0.60	2.30†
500 vs 130 fpm	4.01**	2.38†	4.28**
320 vs 200 fpm	0.23	0.05	1.14
320 vs 130 fpm	2.71†	3.19**	3.44**
200 vs 130 fpm	3.50**	2.40†	2.94**

Thickness

Table Values (df = 22)

Probability *:	0.50	0.40	0.30	0.20	0.10	0.05	0.02	0.01	0.001
Students' t :	0.69	0.86	1.06	1.32	1.72	2.07	2.51	2.82	3.79

2 in. vs 4 in.	0.85	0.21	1.05
2 in. vs 8 in.	2.77†	2.49†	1.81‡
4 in. vs 8 in.	1.78‡	1.63	1.05

* Probability that a t value as large as or larger than the stated value could have occurred by chance.

** The effects differ significantly with a confidence level of 99% or more.

† The effects differ significantly, with a confidence level of 95% or more.

‡ The effects for the two levels of the factor under comparison differ significantly, with a confidence level of 90% or more.

significantly more efficient than the 2-in. bed. This is interpreted as an indication that a considerable increase in bed thickness is required to achieve a significant gain in dust or radon daughters collection efficiency, and the most important consideration is, therefore, the pressure drop across the bed and the corresponding fan requirements (size, power, static pressure, characteristic curve, etc), to achieve the necessary flow rate. Moreover, it appears to be unnecessary to take elaborate measures to insure uniform thickness in spreading the vermiculite on the bed, since variations of 2 in. to 4 in. in thickness have little effect.

The Konimeter measurements are not reported because they were found to be highly erratic and inconsistent with the gravimetric results. In many cases where the gravimetric results indicated a low efficiency the Konimeter data indicated an efficiency close to 100% (the filtered air count approached zero). However, in other cases the particle count in the filtered air was nearly double that in unfiltered air. No reliable conclusions could be based on these data.

The pressure drop across the filtration bed varied directly with bed thickness and face velocity. A graph of this pressure drop vs face velocity for different bed thicknesses at time of testing is shown in Figure 5.

After the data required for the statistical analysis were obtained, the 8 in. filtration bed was operated continuously, with an initial face velocity of 200 ft/min, to observe the effect on the efficiency due to the accumulated dust load on the filter bed. The efficiency vs the total volume of filtered air passed is shown in Figure 6. Each point on the graph is the average of three observations with the standard deviations shown as error bars. The efficiencies and the pressure drop across the filter gradually increased as the flow rate slowly decreased.

After two weeks operation (200×10^6 ft^3) collection efficiencies were in the range from 40 to 60%, the pressure drop had increased by about 60%, and the flow rate had dropped by about 13%.

Summary and Recommendations

Using vermiculite as the filter medium, variation in the collection efficiencies in respirable and total dust, for face velocities in the range of 200 to 500 ft/min, were not statistically significant. However, for radon daughters, there was a significant increase in efficiency from approximately 15 to 30% as the face velocity increased from 130 to 500 ft/min. An increase in bed thickness from 2 in. to 8 in. improved the collection efficiencies in respirable and total dust and radon daughters. For respirable dust, the efficiency increased from 20 to 30% in going from a 2-in. to an 8-in. bed. For total dust it varied from 30 to 40% for a 2-in. to an 8-in. bed and for radon daughters from 20 to 25% for a 2-in. to an 8-in. bed.

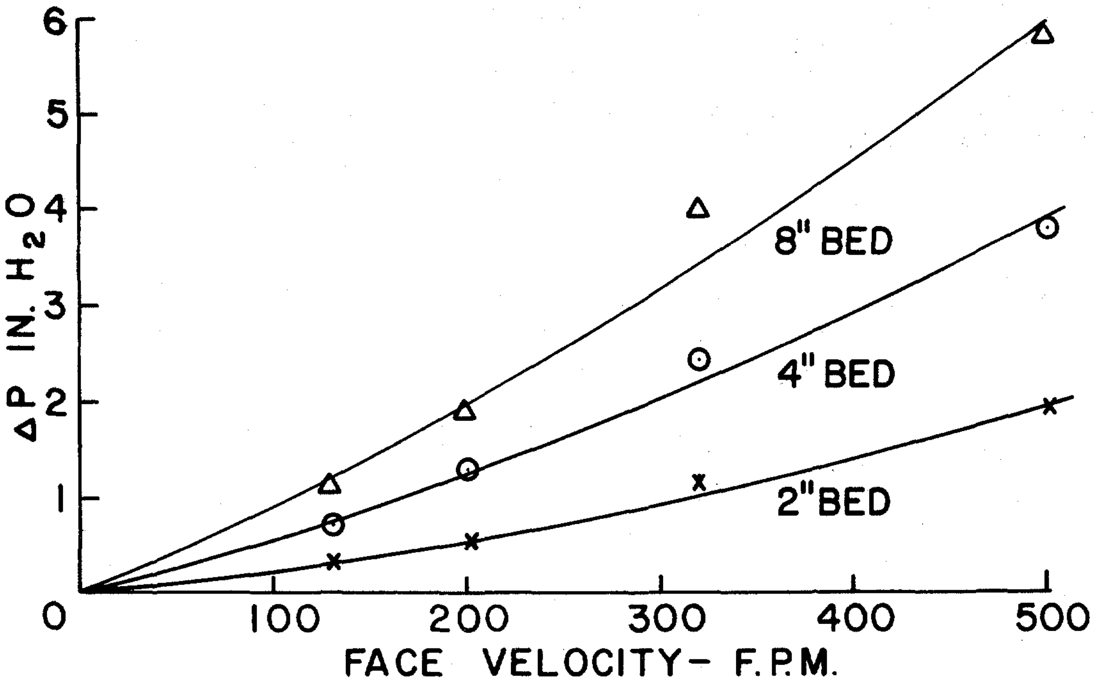

FIGURE 5: PRESSURE DROP vs. FACE VELOCITY

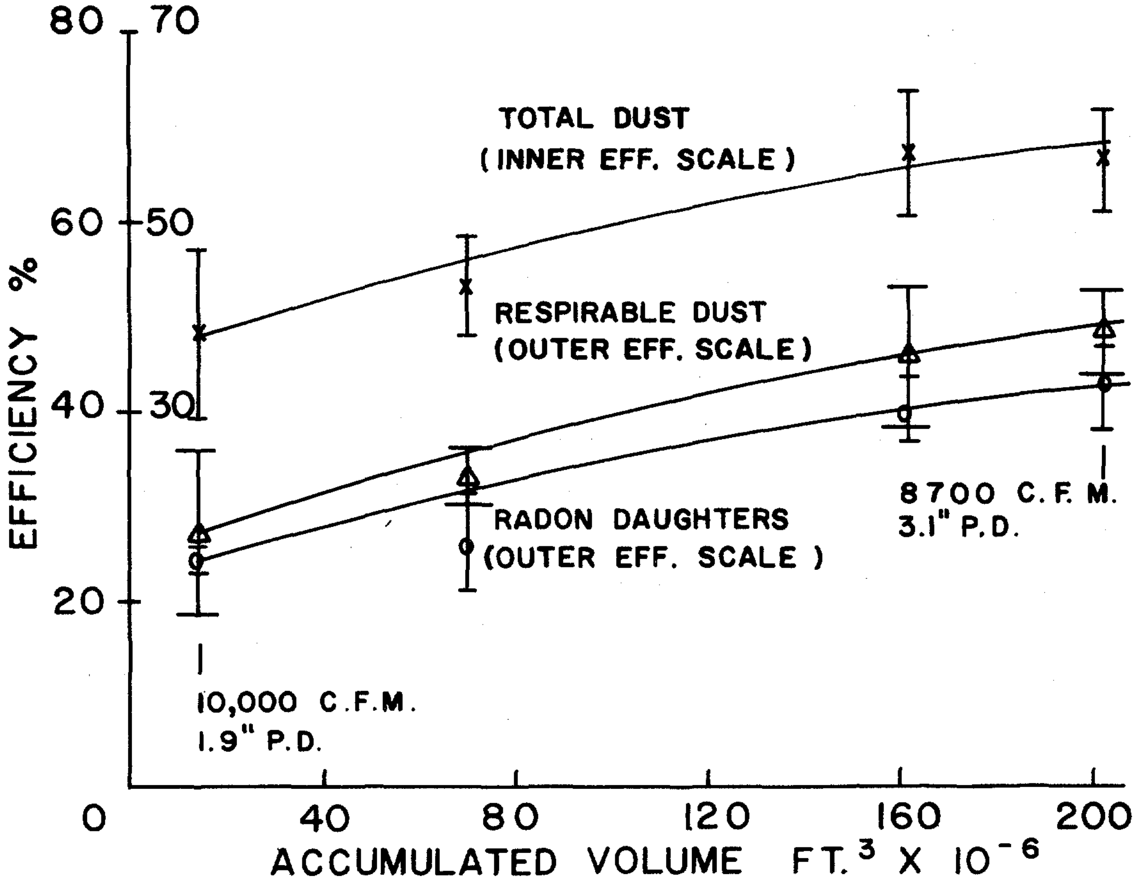

FIGURE 6: EFFICIENCY vs. ACCUMULATED VOLUME

In comparison with some commercial filter materials that have been tested (1) vermiculite has relatively low efficiency. However, there are many factors that make vermiculite more attractive than commercial filters for use underground: (i) low cost (less than $\$1/ft^3$); (ii) low density and ease of handling; (iii) resistance to moisture, (the relative humidity level underground is nearly 100% and moisture tended to be absorbed and adsorbed by many conventional filter fabrics, especially paper, leading to a reduction of pore size, rapid clogging and loss of structural strength, and therefore requiring frequent replacement); (iv) capability of withstanding a high pressure drop, under which many ordinary fabrics would rupture; (v) ease of disposal after use.

From the standpoint of radon daughter removal, it would be beneficial to operate at high face velocity but the high pressure drop would increase the power requirement of the fan, and thus the operating cost. The optimum condition would probably be to operate at a lower face velocity and permit the efficiencies to increase gradually as the filter loads up.

For optimum efficiency, it is suggested an 8-in. bed be used with a face velocity of about 200 ft/min or more. The initial pressure drop should be approximately 1.8 in. The time for replacement will depend upon the condition of the air being filtered. When the pressure drop reaches 5 in., or the limit of the fan (i.e. when the fan approaches a stalling condition), then the filter should be replaced. The materials (e.g. plywood) used for the construction of filter units must be strong enough to stand a moderately high pressure drop and can be greased to prevent warping in damp conditions.

In areas where a 30% to 40% reduction in working level would be sufficient, vermiculite can be the ideal material to be used. In others where a higher reduction is desired, several vermiculite filters in series might be used effectively.

Acknowledgements

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References

1. Kruzich, F. and Washington, R.A., "Mechanical Filtration of Aerosols in Trackless Uranium Mines", IR MR 70/58-LD, April (1970); Washington, R.A., Kruzich, F. and Regan, R., "Mechanical Filtration of Aerosols in Trackless Uranium Mines", II Final Summary, in preparation.

2. Hicks, C.R., "Fundamental Concepts in the Design of Experiments", Holt, Rinehart and Winston, Inc., New York (1964).

3. Kusnetz, H.L., Am. Ind. Hyg. Assoc. J., 17, 1 (1956).

4. Holaday, D.M., Cushing, D.E., Coleman, R.D., Woolrich, P.F., Kusnetz, H.L. and Bale, W.F., "Control of Radon Daughters in Uranium Mines and Calculations on Biologic Effects", U.S. Dept. of Health, Education and Welfare, Public Health Service Pub. No. 494 (1957).

5. Volk, W., "Industrial Statistics", Chemical Engineering J., pp 165-171, March (1956).

6. Threshold Limit Values of Airborne Contaminants. American Conference of Governmental Industrial Hygienists (1971).

7. Knight, G., Personal Communication based on X-Ray Analysis of Dust Samples Collected from Denison Ventilating Air for another study.

8. Guidance for the Control of Radiation Hazards in Uranium Mining. Staff Report No. 8 (revised) of the Federal Radiation Council, Sept. (1967).

9. Schmel, G.A., Am. Ind. Hyg. Assoc. J., 31, 758 (1970).

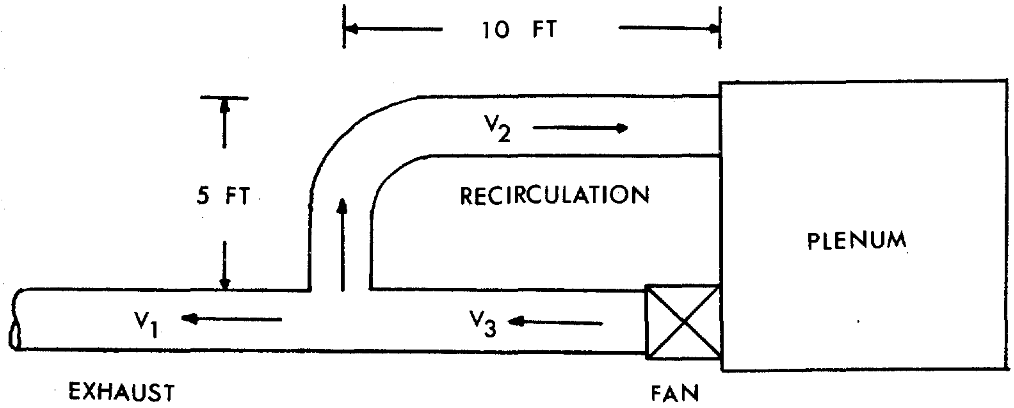
10. Mercer, T.T. and Stowe, W.A., "Radioactive Aerosols Produced by Radon in Room Air", Inhaled Particles III, British Occ. Hyg. Soc. Symp. Proceedings, London, Sept. 1970. Pergamon Press (1971).

11. Blane, D., Fontan, J., Chopries, A., Billard, F., Madelaine, G., and Pradel, J., "Assessment of Airborne Radioactivity", pp 229-237, International Atomic Energy Agency, Vienna (1967).

Appendix A

Effect of Growth or Decay of Radon Daughters for 50% Recirculation

The following calculations are intended to show the effect of growth of radon daughters during recirculation is negligible. The values used for the calculation are chosen so as to project the worst possible case, e.g. in an actual case, there is less than 50% recirculation.



Flow rate in = V_1 cfm = flow rate out >> 1
Recirculation rate = V_2 cfm < V_1 (V_2 >> 1)
$V_3 = (V_1 + V_2)$ cfm

Assume that recirculated air is completely mixed with incoming air in plenum and fan, and that the Rn^{222} concentration in incoming air is $Q\mu\mu$ C/l. If the residence time of air in the system is small relative to the Rn^{222} Half-life of 3.82 days (say 7 hours or less), the decrease in Rn^{222} due to radioactive disintegration will be negligible (less than 5%).

The longest residence time for air in the system occurs when $V_1 = V_2$. In this case, one cubic foot of incoming air is mixed with 1 cubic foot of recirculated air, 1 cubic foot of the mixture (containing 1/2 cubic foot of the incoming air) is exhausted, and 1 cubic foot of the mixture is recirculated. This is mixed with a cubic foot of incoming air, and again divided in two parts, so that on the second recirculation pass only 1/4 cubic foot of the original aliquot remains in the system. Each succeeding pass results in dilution by a factor of 2, so that after 5 passes only about 3% of the original air remains, and about 97% has been exhausted. After 10 passes, only about 0.1% remains, and about 99.9% has been exhausted. If the design value of 10,000 cfm is taken for V_3, and 5000 cfm for V_1 and V_2 respectively, and the duct diameter is 20 in. (i.e. cross sectional area = 2.2 ft^2) then the linear velocity in the exhaust, and recirculation sections of the system is about 2260 ft/min. In the portion of duct immediately after the fan, the linear velocity will be about 4500 ft/min. Assuming the dimensions shown in the diagram for the various portions of the duct, the time required for movement of air through the duct is:

$$\frac{10 + 5}{2260} + \frac{10}{4500} = 0.007 + 0.002 = 0.009 \text{ min},$$

If the plenum volume is 8 ft x 8 ft x 4 ft = 260 ft^3, and the total flow rate in the plenum is 10,000 ft^3/min ($=V_3$) then the residence time of air in the plenum is:

$$\frac{260}{10^4} \text{ min} = 0.026 \text{ min}.$$

Thus the total recirculation time is less than 0.04 min for a single complete pass around the recirculation system. In about 0.5 min, more than ten passes will be completed, and this is far less than the time required for appreciable decay of radon. The radon concentration will therefore remain constant.

Now consider the situation involving radon daughters. If the radon is assumed to be in equilibrium with its daughters in the incoming air, the radon daughters working level will be $Q \times 10^{-2}$. For a filter efficiency of E%, the radon daughters removed will be $E \times Q \times 10^{-4}$ W.L./l and the concentration immediately after filtration will be $(1 - E \times 10^{-2})\ Q \times 10^{-2}$ W.L. Growth of radon daughters begins at once, and after about 30 min RaA will again be in equilibrium. The time required to reach equilibrium for RaB, RaC, and RaC^1 is much greater, and need not be considered at the moment.

While the RaA is being "grown in" again, however, it is being diluted by a factor of two on each recirculation pass. A single pass requires ca. 0.04 min, and in this period the RaA increases by ca. 1%. Dilution then occurs, reducing this figure to about 0.5%. This has the practical effect of doubling the apparent half-life of RaA for the purpose of regrowth, and therefore doubling the time required to reach equilibrium.

It has been shown that the residence time of air in the system is only about 0.5 minutes, and during this time only about 10 to 11% of the RaA removed by filtration will grow back, if no dilution takes place. Allowing for the effect of dilution by recirculation (by assuming the half-life to be doubled) leads to a value of 5% for the fraction of filtered RaA which grows back. Since the error in the efficiency measurement was estimated to be of the same order, it can be assumed that the error due to regrowth of radon daughters could be neglected.

DISCUSSION

THOMAS, J: I would like to ask you the same question that I asked Bob Rock. Suppose you had a moderate maintenance cost system that would take out radon gas at 2500 cfm; would you be willing to say whether such a device would be worth a thousand dollars, or three thousand, or ten thousand? There is no point in developing a device unless people are willing to pay for it and use it.

WASHINGTON: I really have no idea what the mines would be willing to pay for such a system. I think they will pay as much as they need to pay to get the air quality that is required of them by the regulations. What it gets down to, as Bob said, is a matter of dollars and cents. If they can clean up the air and still produce uranium at a profit, they will do it. If the ventilation costs rise so high that it becomes prohibitive, some operators may close down operations. Then, the cost of uranium may go up. I couldn't say any closer than that.

ETTINGER: I want to comment on Mr. Thomas' question. I think the answer is going to be set by the Federal Government. They are the major purchaser, and if they specify a 0.2 to 0.3 working level, they must be willing to pay the price, and the mine owners will have to do it. In our country the AEC will do this, and I assume a similar establishment in Canada will be the ones who will apply pressure to the mine owners. They will say, "You must get the working level down, or we will shut you down." The mine owners will probably respond by raising the price.

THOMAS, J: After thinking it over, it looks like the answer to the question I posed depends on whether it is cheaper to put a device costing five or ten thousand dollars down in a mine to remove radon, or cheaper to put in more air ventilation.

REVIEW OF PROBLEMS AND TECHNIQUES FOR REMOVAL OF RADON AND RADON DAUGHTER PRODUCTS FROM MINE ATMOSPHERES

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Abstract

Ventilation with fresh air has been, and will continue to be, the primary solution for controlling employee exposure to radon and radon daughters in mines. Procedures to make the ventilation process more effective and to reduce contamination have been proposed; such as mine pressurization, construction of effective stoppings to seal old workings, and coatings to reduce radon inflow.

Cleaning of mine air has been successful in certain applications. Removal of radon daughters can be accomplished by mechanical filtering and by electrostatic collection. Both of these methods remove condensation nuclei to which radon daughters become attached. Radon gas which passes through continues to decay; however, in the absence of condensation nuclei, the daughters have large diffusion lengths and are trapped on the walls of air courses. Thus the growth of daughters after filtering may be less than previously calculated without accounting for diffusion losses.

Radon gas, itself, has been successfully removed from air, although there are no known reports of this having been done in operating mines. Capture in activated charcoal and silica gel has been accomplished. Chemical removal by reacting with a halogen fluoride and a metal fluoride has been demonstrated.

I. Introduction

The purpose of radioactivity removal from mine atmospheres is to prevent miners from receiving excessive exposure. Exposure to radioactive aerosols in uranium mines has been correlated with an excess incidence of lung cancer.(1) The Bureau of Mines, following recommendations of the Administrator of the Environmental Protection Agency, has promulgated mandatory standards limiting miners' exposure to radon daughters. Basically, the standard is that no employee shall be permitted an annual exposure in excess of four working level months (WLM).

A working level (WL) of radon daughter concentration is that quantity of Po(218), Pb(214), Bi(214), and Po(214) in a liter of air that will result in the emission of 1.3×10^5 Mev of alpha energy upon their complete decay to Pb(210). This definition is independent of daughter ratios, but one working level results from 100 picocuries of Rn at equilibrium with its daughters. One working level month is an exposure unit equivalent to an individual breathing a concentration of one working level for 173 hours. It is the cumulative product of the time spent in a given concentration multiplied by the concentration.

Radon(222) originates from the decay of Ra(226) which is produced in the decay of uranium(238). Thus, radon occurs in every underground uranium mine. However, it is not limited to uranium mines. Radon is soluble in water and has been known to be carried into mines with essentially no uranium in the native rock or ore. The decay scheme of uranium is shown in figure 1.

II. Radon Emanation and Radon Daughter Growth

Radon may enter the mine atmosphere by diffusion from the rock surrounding mine passages or by escaping from mine water or by both. Water in contact with air containing radon will, at equilibrium, contain approximately one-third the radon per unit volume as the air at room temperatures. Thus, water with dissolved radon will readily contaminate clean air.

The transport of radon in the mine rock follows Fick's law:

$$J = - D \nabla C$$

where J is radon flux in $Ci/cm^2/sec$,

D is the diffusion coefficient in cm^2/sec,

and ∇ C is the bulk concentration gradient of radon in the rock.

For sandstone with $\sim$ 20 percent interstitial volume, D $\approx$ 0.02 cm^2/sec. The relaxation length for radon in sandstone is given by

$$\frac{1}{\alpha} = \sqrt{\frac{\lambda}{D}} \qquad \lambda = \text{decay constant of radon.}$$

$$\alpha = \sqrt{\frac{0.02\ cm^2\ sec^{-1}}{2.1\ x10^{-6}\ sec^{-1}}} \sim 100\ cm$$

Thus, radon diffuses from considerable depth into the mine openings.

Figure 2, taken from Schroeder and Evans(2), illustrates this effect. Other rock with considerably less interstitial volume will show a much shorter relaxation length.

Radon fluxes have been measured ranging from about 5 x 10^{-14} $Ci/cm^2/sec$ down to 5 x 10^{-16} $Ci/cm^2/sec$. The latter figure is from the Elliott Lake region of Ontario, Canada, where the rock porosity is low, probably less than 1 percent.

Control of radon inflow will be discussed later, after a description of the generation and behavior of radon daughters following radon decay. Schroeder and Evans(2) have derived a formula for predicting radiation levels in a uniform tunnel assuming a uniform flux of radon (J) from the tunnel surfaces. The growth of radon daughters (WL) in air containing fresh radon may be approximated by

$$WL \sim K\ t^{0.85}$$

where K is a proportionality constant and t is the time.

$$K \sim 0.023\ WL\ \text{per (100 pCi Rn per liter)}\ min^{-0.85}$$

The formula for the daughter concentration at any point in the tunnel is given by

$$WL \sim \frac{JPK}{1.85A} \qquad T^{1.85}$$

where J is the radon flux,

P is the perimeter of the tunnel cross section,

A is the area of the tunnel cross section,

and T is the time for the air to reach any given point of the tunnel.

Thus the concept of "age of air" is illustrated. The growth of radon daughters is seen to be nearly the square of the residence time. This formula does not account for any losses of radon daughters due to attachment to tunnel surfaces.

Radon daughters readily become attached to solid surfaces. Therefore they are usually attached to aerosol particles in the mine atmosphere. Many experimental studies of attachment have been reported. Raabe has found that activity is proportional to the surface area of the aerosol particles, and in the laboratory the majority of the activity is associated with particles less than 0.1 micrometer diameter.(3) Aerosols in mines contain many components - diesel exhaust, mineral dust, drill oil mist, water droplets, blasting fumes, etc. The Bureau of Mines has contracted with Battelle Northwest to investigate the characteristics of uranium mine aerosols.

Attached daughters have short diffusion lengths and therefore are not readily removed by mine surfaces. Unattached daughters, however, have long diffusion lengths and will migrate to and be captured on mine surfaces.(4) These considerations will have significance in filtering mine air.

III. Radon Daughter Removal

Ventilation with fresh air has been, and will continue to be, the primary method of controlling miner exposure to radon daughters. The growth of WL in air with fresh radon is illustrated in figure 3. Therefore, if air containing 1000 pCi/liter of radon is scrubbed through filtration, the daughter concentration will grow to 0.6 WL in 3 minutes and to 1.6 WL in 10 minutes. The curve in figure 3 was derived neglecting the removal of daughters by attachment to mine surfaces. Since filtration will remove a significant fraction of the condensation nuclei, the diffusion of daughters to mine surfaces is significant. This effect is felt to be quite important in the success of filtration as it is practiced. An analysis of the diffusion of radon daughters to mine surfaces is given by Wrenn et al.(4) This analysis is highly idealized and has not yet been applied to practical situations. Mechanical filtration has been an effective means of radon daughter removal. Problems associated with filtration are the dust loading, oil mist loading, water vapor saturation resulting in deterioration, and radioactivity buildup. The latter has not caused serious problems but is related to the length of time a filter is used. Disposal is usually accomplished by discarding the old filters in abandoned workings. Figure 4 lists efficiencies of various filters and sand beds for radon daughter removal reported by Frame.(6) Measurements of the degree to which the radon daughters are captured on mine surfaces following filtration have been reported by Shreve and Cleveland.(7) Figure 5 illustrates the uncombined daughter fraction vs particle concentration in unfiltered mine air.(8)

Swindle has reported on the use of electrostatic precipitators for air filtering.(9) Efficiencies obtained by Swindle for removing radon daughters are shown in figure 6.

Figure 7 illustrates the efficiency of radon daughter capture by mine surfaces.(10) The data taken before shift represent relatively clean air, whereas during shift the aerosol concentration is increased due to mining activity. Figure 8, also due to Swindle,(10) compares activity ratios of individual daughter products to the theoretical model of Thomas and Epps.(11) Indications of capture by mine surfaces are that most points are below the theoretical curve. Rather long residence times are also noted. This is probably due, in part, to the addition of near-equilibrium air from stagnant areas of the mines.

Research efforts are presently being conducted to develop new filtering media. Existing filters have short life and relatively high resistance. The Bureau of Mines is investigating the properties of plastic beads in bed-type filters. These bed filters are capable of removing over 90 percent of the radon daughters. Their life and increased resistance with dust loading and efficiency after use are being investigated.

IV. Radon Emanation Control

The use of sealing materials to coat mine surfaces and reduce radon inflow is an immediate thought. However, the problem has been considered by many, and the only practical application has been to provide sealed stoppings for worked-out areas that no longer require ventilation. This application is used by nearly all mining companies.

The use of sealants for gross coating of mine surfaces has, to my knowledge, never been successful. Some commercially available coatings have been screened by the Bureau of Mines Technical Support Center in Denver. This screening is rather simple. It consists of placing a sample of ore in a radon counting flask and recording the counts as a function of time. Then the same piece of ore is coated with the candidate coating and allowed to dry. Then the same counting process is repeated. Although the method is neither very scientific nor rigorously controlled, the results have not been very encouraging. Figure 9 shows some typical results obtained by Beckman.

Another method of controlling radon inflow is to pressurize the mine workings.(2) This technique does indeed reduce the radon inflow. The method has never been reduced to practice because of a number of practical problems. The greatest problem is the operation of a mine under pressure. It has never been determined where the radon is deposited in this kind of operation. If the porosity of the earth is such that the radon migrates to the surface, no difficulties are foreseen. However, if other sinks are important, will they fill after a time? Is the radon forced from high pressure parts of the mine to regions of lower pressure? Other questions may be asked, not all of which are necessarily unanswerable.

V. Radon Removal

Techniques for removing radon gas from mine atmospheres have been reported.(12) (13) (14) The method proposed and tested by Reiter(12) is to capture radon on silica gel using oil to transfer the radon from the air to the silica gel. Figure 10 illustrates the apparatus constructed by Reiter. The purpose of the oil is to absorb radon from air. The radon then migrates to silica gel where it is trapped and decays. The solubility of radon in some oils is much greater than in air or most other liquids. For example the solubility coefficient for radon in olive oil at 37°C is 19.0.(15) The solubility coefficient is the concentration in solution divided by the concentration in air at equilibrium. Reiter used tricresyl meta phosphate which has a solubility coefficient of 4.3 at 20°C. In tests in a chamber, the radon concentration was reduced to a value 75-80 percent lower than initially present after about 17 circulations of the chamber volume.

Stein(14) has developed chemical compounds that react chemically with radon. These compounds are bromine trifluoride and solid complexes ClF_2SbF_6, BrF_2SbF_6, $BrF_4Sb_2F_{11}$, $IF_4(SbF_6)_3$, and BrF_2BiF_6. Unfortunately, these compounds are also reactive with water vapor and perhaps diesel exhaust components. The reaction products are highly toxic and the air would require scrubbing and purification after passing through the chemical. Also, if the chemical is not to be consumed by reaction with water, the air must be dried before passing through the cleaning process. No practical drying process known will reduce the water vapor to a concentration equivalent to the radon concentration $\sim 10^7$ atoms per liter. Thus, most of the chemical will be consumed by the undesired reaction with water.

The trapping of radon and letting it decay in a concentrated volume may result in a highly radioactive material which must be disposed of. For example, if the radon concentration of 1000 pCi/liter is passed through a trap at 1000 cfm the activity of Pb(210) at the end of one month will be over ½ millicurie.

A method of cryogenic removal of radon has been patented by Howell. This method depends on the condensation of air while the very rarefied radon will remain in the gaseous phase. Figure 11 is a schema of the process proposed by Howell. This method has not been tried in a mine and for it to be practical, much of the energy of condensation would have to be returned to the evaporating liquid. The radon-rich phase would be exhausted from the mine in a small stream. Enough fresh air would be required to make up this exhaust air.

The cryogenic method would appear to have no unusual engineering difficulties. The practical application would appear to depend on the installation and operation costs.

The Bureau of Mines has requested an assessment of the feasibility of using a gas centrifuge for radon removal. The separation factor for centrifugal separation is given by

$$r = \exp \left[v^2(M_2-M_1)/RT \right]$$

where v is the peripheral speed of the centrifuge,

M_2-M_1 is the mass difference of the gases to be separated,

R is the gas constant,

and T is the absolute temperature.

For the mass difference between radon ($M_2 = 222$) and air ($M_1 = 30$), very large separations can be obtained with reasonable peripheral speeds.

In an analysis by Keller(16) several difficulties were pointed out. Without elaboration, these difficulties are-

1. Large units approximately 4 feet in diameter would be required to get necessary air throughout - 1000 cfm or more.
2. To treat an air flow of 1000 cfm (~ 82 pounds air per minute) would require more than 50 HP input to supply the total energy to the rotating gas.
3. Because of the long equilibrium times at atmospheric pressure, a single-pass centrifuge would not be feasible; i.e., a 10-minute residence time would result in only about 50-percent equilibrium.

Other lesser but serious design problems would have to be solved before the method would be feasible.

VI. Conclusion

Ventilation with fresh air undoubtedly will be the primary method for controlling radiation levels in mines. This is a well-understood technology that is currently practiced in all uranium mines.

Removal of radon daughters has been and will be a useful technique for enhancing ventilation in situations where conventional ventilation is extremely difficult or expensive.

Sealing and radon gas removal will probably not be developed without substantial increase in the costs of mining and an equivalent increase in the price of uranium.

It is technically feasible to use all three control techniques; i.e., reduction or prevention of radon inflow (sealants or pressurization), radon daughter removal, and radon gas removal.

REFERENCES

1. Lundin, F. E., J. K. Wagoner, and V. E. Archer. Radon Daughter Exposure and Respiratory Cancer, Quantitative and Temporal Aspects. U.S. Department of Health, Education, and Welfare, Public Health Service, NIOSH-NIEHS Joint Monograph No. 1 June 1971. Available from National Technical Information Service, U.S. Department of Commerce, Springfield, Va. 22151.

2. Schroeder, G. L., and R. D. Evans. Some Basic Concepts in Uranium Mine Ventilation. Trans. Soc. Min. Eng. AIME, v. 244 September 1969.

3. Raabe, O. G. Concerning the Interactions That Occur Between Radon Decay Products and Aerosols. Presented at Uranium Mining Health Physics Workshop, Denver, Colo. June 1968.

4. Wrenn, M. E., M. Eisenbud, C. Costa-Ribeiro, A. J. Hazle, and R. D. Siek. Reduction of Radon Daughter Concentrations in Mines by Rapid Mixing Without Makeup Air. Health Physics, v. 17 (1969)

5. Wrenn, M. E., J. C. Rosen, and W. R. Van Pelt. Steady State Solutions for the Diffusion Equations of Radon 222 Daughters. Health Physics, v. 16 (1969)

6. Frame, C. H. Ventilation Practices at Denison Mines Limited. Canadian Min. J. (1969)

7. Shreve, J. D., Jr., and J. E. Cleveland. Effects of Depressing Attachment Ratio of Radon Daughters in Uranium Mine Atmosphere Control. American Industrial Hygiene Conference, Toronto (1971)

8. George, A. C., and L. Hinchliffe. Measurements of Uncombined Radon Daughters in Uranium Mines. Health Physics, (in press).

9. Swindle, R. W. Radon Daughter Control Methods for Underground Mines: A Provisional Evaluation. Conference on the Underground Mining Environment, Rolla, Missouri (1971)

10. Swindle, R. W. Radon Daughter Control in Uranium - Vanadium Mines in the Uravan Mineral Belt. American Industrial Hygiene Conference, Toronto (1971)

11. Thomas, J. W., and R. Epps. Radium A, B, and C Concentrations and Working Levels From Radon Emanation in a Mine Tunnel. U. S. Atomic Energy Commission, Report HASL 70-4 September 1970

12. Reiter, R. Devices and Precautions for Protection Against Radon and Its Decay Products in Mine Atmospheres. Nucleonik, v. 9 (1967)

13. Howell, W. P. Method for Purification of Radon Containing Air. U.S. Pat. No. 3,606,760.

14. Stein, L. Chemical Methods for Removing Radon and Radon Daughters from Air. Science, v. 175 (1972)

15. Von Dobeln, W., and B. Lindell. Some Aspects of Radon Contamination Following Ingestion. Arkiv fur Fysik, v. 27 (1964)

16. Keller, C. A. Private Communication to U.S. Atomic Energy Commission; forwarded to Bureau of Mines.

$$^{238}\mathrm{U} \xrightarrow[4.51 \times 10^{9}\ \mathrm{yrs}]{\alpha} {}^{234}\mathrm{Th} \xrightarrow[24.1\ \mathrm{days}]{\beta,\gamma} {}^{234}\mathrm{Pa} \xrightarrow[6.66\ \mathrm{hrs}]{\beta,\gamma} {}^{234}\mathrm{U} \xrightarrow[2.48 \times 10^{5}\ \mathrm{yrs}]{\alpha}$$

$$^{230}\mathrm{Th} \xrightarrow[7.6 \times 10^{4}\ \mathrm{yrs}]{\alpha} {}^{226}\mathrm{Ra} \xrightarrow[1620\ \mathrm{yrs}]{\alpha} {}^{222}\mathrm{Rn} \xrightarrow[3.82\ \mathrm{days}]{\alpha} {}^{218}\mathrm{Po}\ (\mathrm{RaA}) \xrightarrow[3.05\ \mathrm{mins.}]{\alpha}$$

$$^{214}\mathrm{Pb}\ (\mathrm{RaB}) \xrightarrow[26.8\ \mathrm{mins.}]{\beta,\gamma} {}^{214}\mathrm{Bi}\ (\mathrm{RaC}) \xrightarrow[19.7\ \mathrm{mins.}]{\beta,\gamma} {}^{214}\mathrm{Po}\ (\mathrm{RaC'}) \xrightarrow[164\ \mu\mathrm{sec.}]{\alpha}$$

$$^{210}\mathrm{Pb}\ (\mathrm{RaD}) \xrightarrow[21\ \mathrm{yrs.}]{\beta,\gamma} {}^{210}\mathrm{Bi}\ (\mathrm{RaE}) \xrightarrow[5.0\ \mathrm{days}]{\beta} {}^{210}\mathrm{Po}\ (\mathrm{RaF}) \xrightarrow[138\ \mathrm{days}]{\alpha} {}^{206}\mathrm{Pb}\ (\mathrm{Stable})$$

FIGURE 1.- The Decay Scheme of Uranium

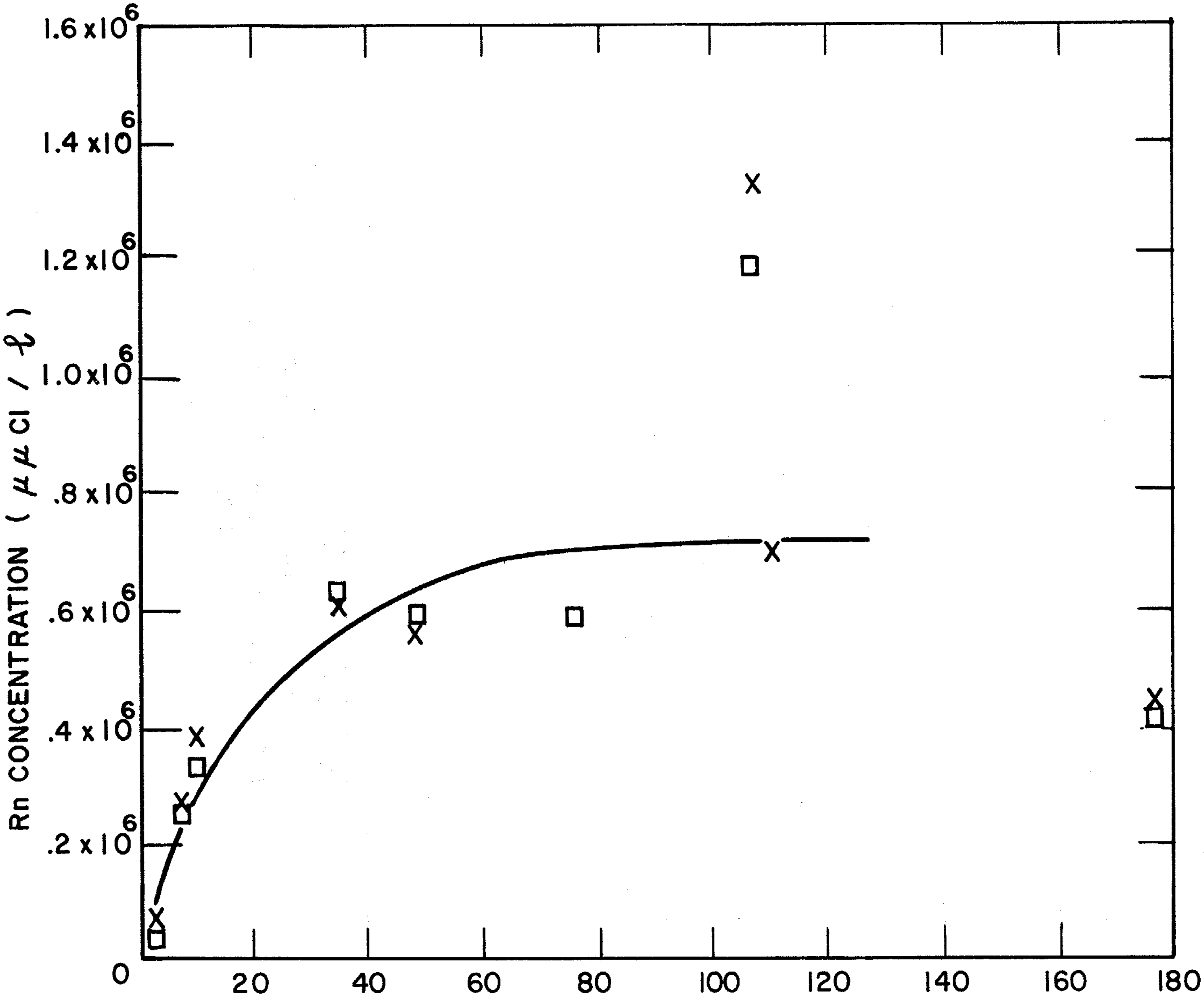

Figure 2. – Interstitial radon concentration vs. depth at a location of low grade ore.

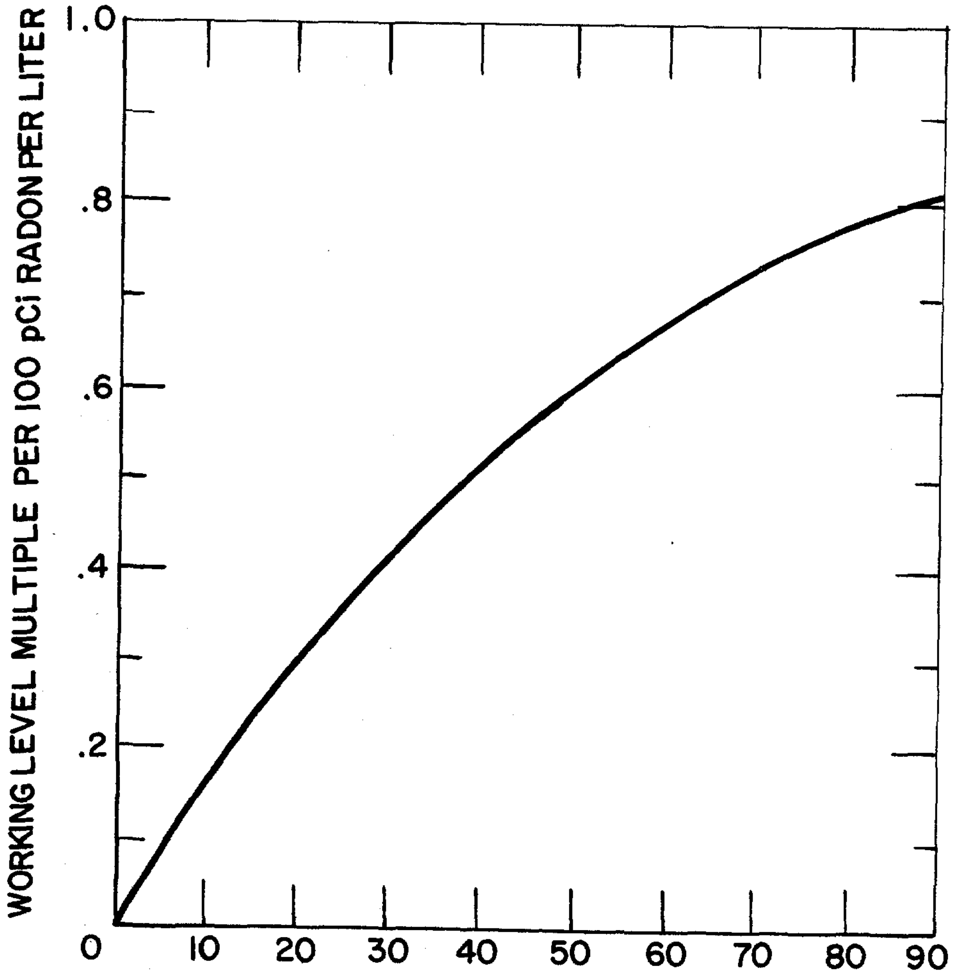

Figure 3. - Growth of daughters from airborne radon daughter removal.

Type of filter	'Life' of filter (million cu ft)	Pressure drop (in w.g.) Initial	Final	Avg. (cfm.)	Avg. face velocity (fpm.)	Avg. Dust removal % Total	Respirable	Avg. radon daughter removal %	Commercial efficiencies %
Fibrous filter									
No. 1 (1)	5.87 (2)	0.47	5.90	523	130	98	99	97	99 (dust spot) 95 (smoke test)
No. 2	2.16	2.40	4.85	750	187	64	63	47	99 (weight method)
No. 3	6.98	0.24	4.00	625	156	46	38	24	90 (weight method)
Sand bed									
No. 1 (3)	9.45 (5)	2.50	4.00	225	19	80	86	85	
No. 2 (4)	7.28 (5)	1.00	2.00	300	25	50	55	60	

1. Main filter and prefilter.
2. Average total dust loading = 1.37 mg/m^3 (vitiated air). Avertised service life without prefilter in typical industrial city air = 200 million cubic feet at 1.0 w.g. final pressure drop.
3. Thickness of bed = 7 inches. Filter medium = 1M New Jersey silica sand. Effective size = 0.6 to 0.8 mm., uniformity coefficient = 1.6.
4. Thickness of bed = 5 inches. Filter medium = 2M New Jersey silica sand. E.S. = 0.8 mm. to 1.2 mm., U. C. = 1.6.
5. Total volume for which Sand Bed was tested.

FIGURE 4.- Efficiencies of Various Filters and Sand Beds for Radon Daughter Removal.

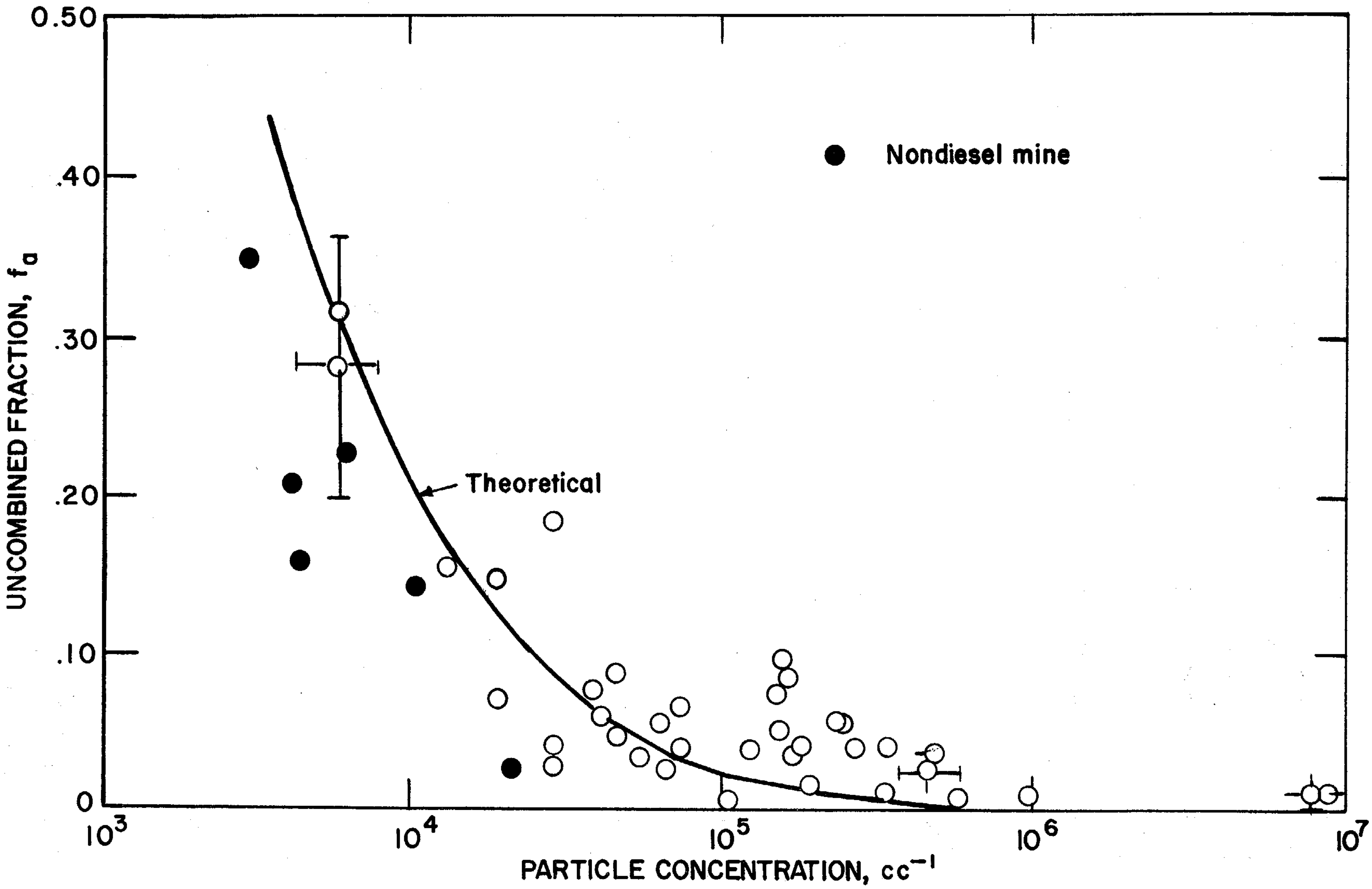

Figure 5. -Variation of uncombined fraction with particle concentration.

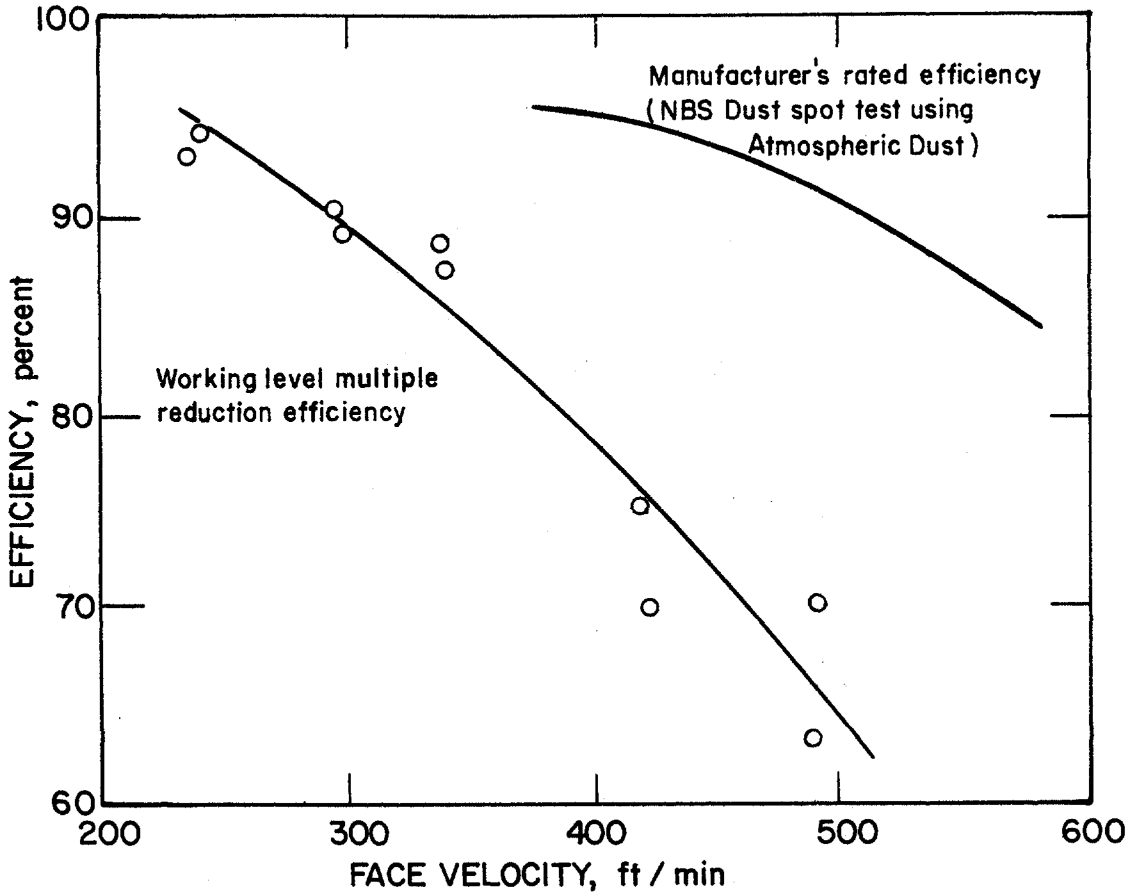

Figure 6. – Effect of Air Velocity on electronic air cleaner (Westinghouse Model PM Precipitron) efficiency.

Mine	$\frac{\text{Working Level Multiple x 100}}{\text{Rn Activity (pCi/liter)}}$ Before Shift	During Shift	$\frac{\text{RaA Activity}}{\text{Rn Activity}}$ Before Shift	During Shift
Nil	0.13	0.44	0.14	0.71
Burro	0.10	0.38	0.12	0.69
Deremo (No. 1 Shaft)	0.04	0.40	0.05	0.62

FIGURE 7.- Effects of Mining Operations on Radon Daughters in Primary Exhaust Air.

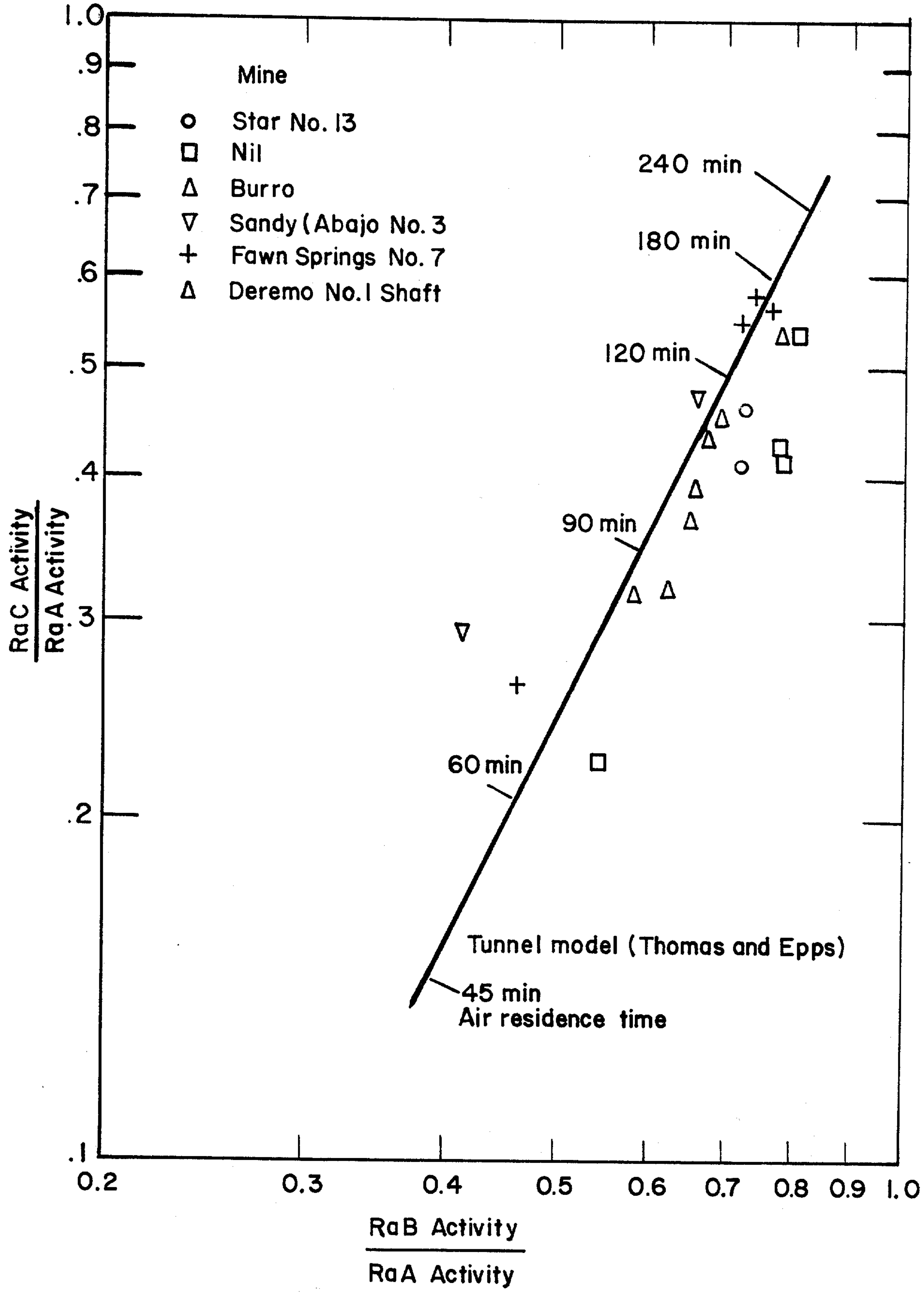

Figure 8.—Comparision of radon daughter mixtures in exhaust air from tunnel model and Uravan Mineral Belt mines.

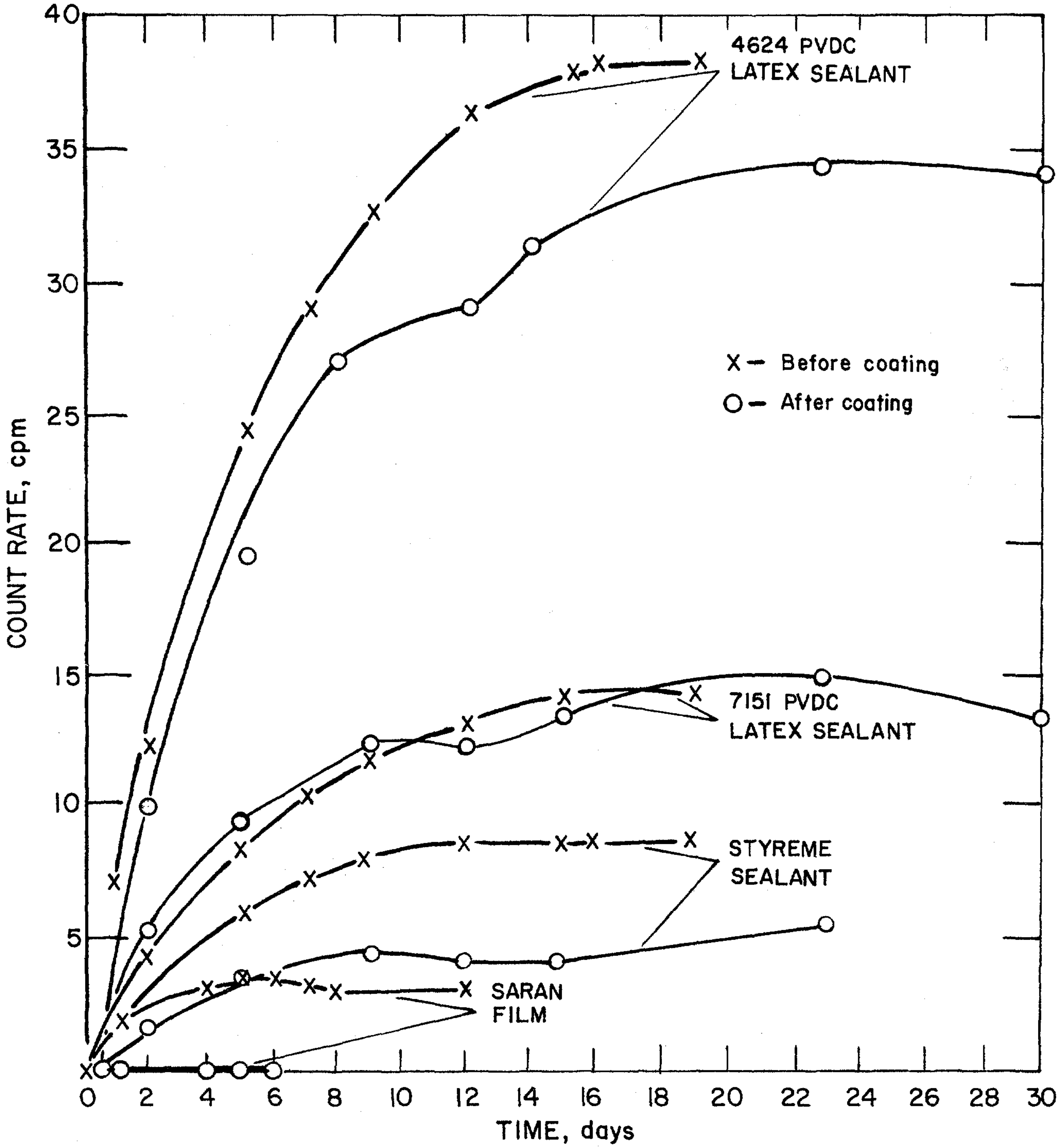

Figure 9. – Typical Results of Effectiveness of Sealants on Ore Samples.

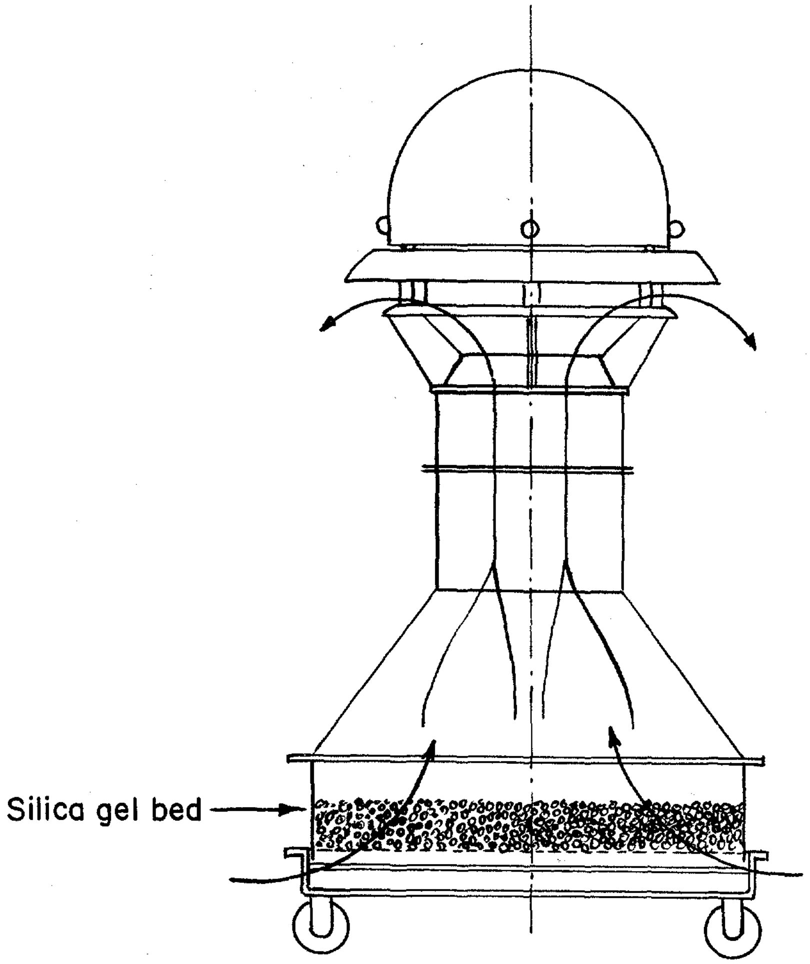

Figure 10.—Apparatus Constructed by Reiter for Removal of Radon Gas from Mine Atsmospheres.

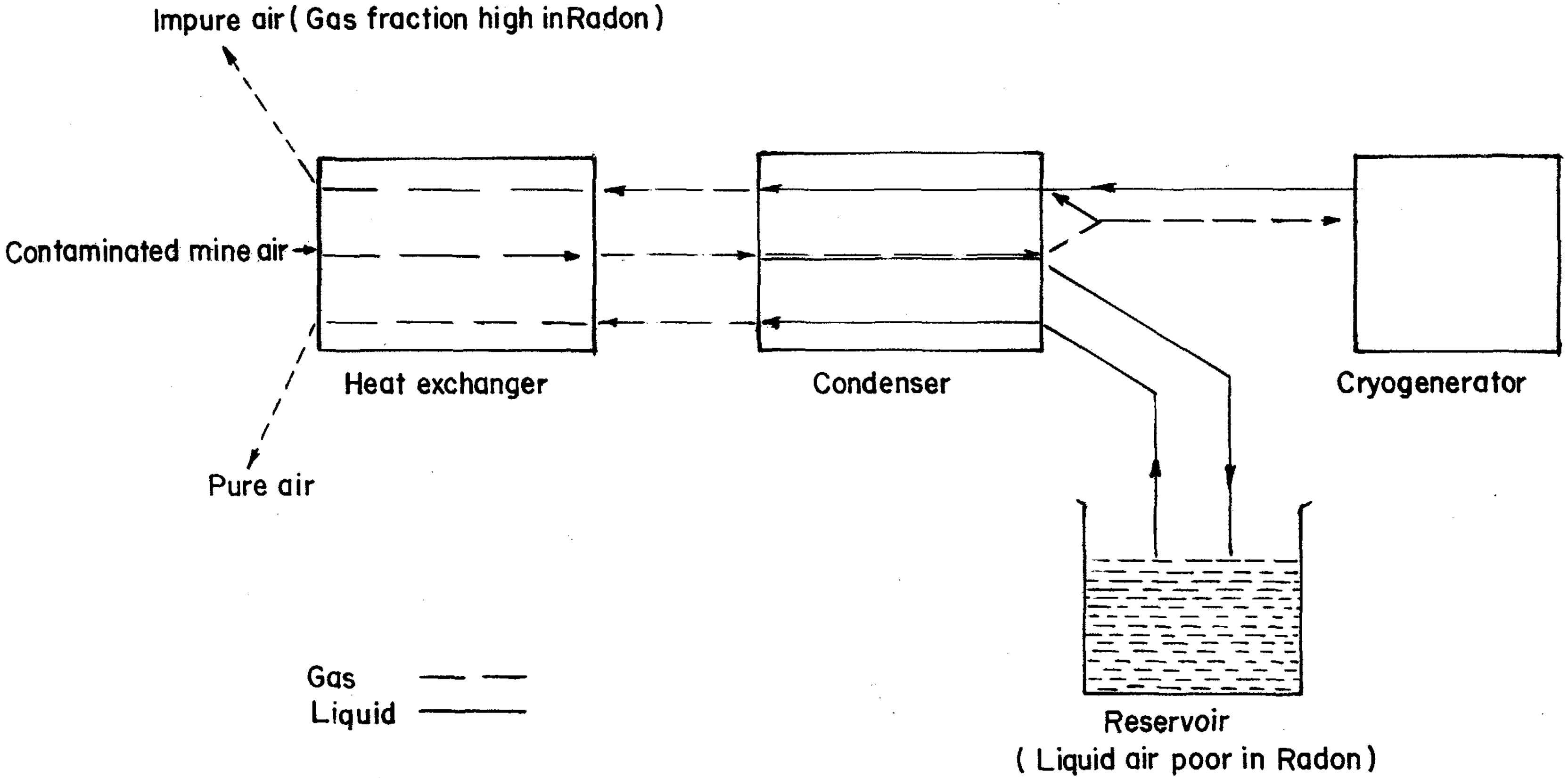

Figure 11. - Schematic of Cryogenic Process for Removal of Radon from Air.

DISCUSSION

LINDSAY: I'd like to answer a couple of questions that have been raised from time to time and to make several comments coming out of my own biases. We made a study a couple of years ago on the feasibility of reducing radon daughter concentrations in uranium mines, and what the cost impact would be all the way down to the consumer who turns on the light switch in his room. If I remember that report correctly, our economists said that, projecting power needs and sources for the next 20 years or so, you could put many multiples on the cost of ventilating a uranium mine. Society would pay for it and it really didn't make much difference how expensive it got. We will need the uranium and we will pay whatever it costs. That was point one.

Point two was that there is a transition period between the time when the government is the principal customer and when private enterprise becomes the principal customer during which the uranium industry is hurting. With the stockpile of surplus government uranium sitting in Grand Junction, some uranium producers feel threatened about what might happen to the commercial market. That creates a temporary situation which is a bit rough on the uranium mines. Still, it is hard to say that the ventilation costs which seem so threatening to the mining companies necessarily make a difference in their survival because there are many other considerations that enter into whether to keep a mine open or not. In the interim period, there may be a threat, but it is a hard one to pin exclusively on ventilation costs.

A final point; I think it was our conclusion that just bringing more fresh air down the shaft is not the solution. When people say it is impossible to ventilate a mine down to 0.3 working level everywhere, all the time, I can believe that for some mines. Bringing more fresh air down a mine involves many other problems that can be self-defeating under extreme circumstances. But, I will go with air management. Air management is something that could stand quite a lot more sophistication. Control of pressure gradients and the control of air movement within the mines is something that, in my personal opinion, really has not been pushed anywhere near far enough in the average working mine in the United States today. All this talk about removal of radon by centrifuging, or chilling, or removing the radon daughters by first taking all the condensation nuclei out of the air of an operating mine are things that we took into consideration. I am dissatisfied with all of them. Their cost effectiveness is miserable. They may not even be technically feasible. It seems to me that all of these approaches have little practical significance in comparison to intelligent air management. I don't believe that additional fresh air is the whole answer. In fact, our study showed that some mines had more fresh air than they needed, provided it was used effectively underground. Leakage from worked-out stopes should be prevented; not by sealing alone, but by controlling pressure differentials across the brattices. This has to be done carefully, particularly in United States mines where the porosity of the sandstone is so high that the area round a brattice may pass more radon than the inevitable leaks in the brattice itself. Passive sealing under such conditions is quite inadequate. When you get down into the mines and see what the real situation is, I think you will agree that, except for filtration to remove attached radon-daughters in certain limited instances, most of the methods that have been proposed have little practical significance compared to good air mangement.

CRAIG: I want to take a completely different tactic, here. As someone who is an international toxicologist involved with the inhalation of all sorts of very hazardous materials including radon, daughter products of radon, and so on, I am very disappointed that not one person has mentioned helping the person who is inhaling the mine air contaminants. I think it would be advisable for somebody in the Bureau of Mines or their funding agencies to give somebody enough money to work on filtering the air that the miner breathes at the point at which he breathes. The miner is already required to wear a hard hat. He also has to wear a lamp. Isn't it possible to work on providing suitable fresh air supplies for the people working in the mines?

GOODWIN: In some operations, miners do wear supplied air respirators, especially where they remain in relatively fixed locations. They do it, primarily, by their own choice because it is dusty and, moreover, quite often miners will ask for respirators just because of Diesel fumes. We are not opposed to providing a clean environment to the miner by such devices provided that miners will accept and use them. I think rejection by miners has been the major problem with most respiratory devices to date.

BLANKO: To continue with this discussion, assuming that money is not the primary consideration and that air control is optimized, what is the most technically feasible additional solution that you would recommend at this time? In the past, many industries have not been willing to use new technology because of economic reasons. However, new technology is now being used because of changes in regulations.

GOODWIN: I am not in the part of the Bureau that does the funding on research projects; although I hope I have some influence. I don't really know. Of all the things that I know about, none looks very practical. I think it would depend very greatly on the approach and the particular proposals that were made. As far as cleaning radon gas out of a mine, I think that's pretty far off, if ever. With respect to radon daughters, whatever is proposed will have to compete with precipators or commercially available filters. A suitable substitute could be vermiculite or something else. The Bureau is working on a deep bed filter, containing plastic foam beads, which is similar to what Bob Washington described using vermiculite. It has to have low resistance, relatively long life, and slow resistance buildup as it picks up dust. It has to operate in a humid atmosphere that is sometimes hot and sometimes cold. This is a rather severe environment for paper filters and they deteriorate rapidly.