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EVALUATION OF BULKHEADS FOR RADON CONTROL

Contract H0212003
Arthur D. Little, Inc.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR
Minerals Health and Safety Technology

DISCLAIMER

FOREWARD

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts under USBM Contract H0212003. The contract was authorized by and executed pursuant to the provisions of Public Law 91-173 (83 STAT. 799) as amended by Public Law 95-164 (91 STAT. 1320), and funded pursuant to Department of the Interior and Related Agencies Appropriations Act (Public Law 96-514) dated December 12, 1980. It was administered under the technical direction of the Spokane Research Center, with Mr. John C. Franklin acting as Technical Project Officer (TPO). Mr. Kent Charles was the contract administrator for the Bureau of Mines.

The contract was initiated in May, 1981, and the field work in the LaSal Mine of Union Carbide Corporation was completed in April, 1982. The first draft of this report was submitted in July, 1982.

The authors wish to acknowledge the helpfulness of the Union Carbide Corporation in making a test site available, and for the excellent co-operation and assistance of Mr. Niels Haubold, Manager of Mines, Mr. Roger Swindle, Staff Mining Engineer, and Mr. Bruce Green, Superintendent of the LaSal area mines. We are especially grateful to Mr. Frank Barnett, LaSal Mine Foreman and Mr. Gordon Sampson, Safety Engineer for their much-needed assistance in the performance of this contract.

The fact that we were able to conduct the field work portion of this contract with a one-person field crew was due in large part to the support we received not only from the operating staff of the LaSal mine, but also from personnel of the USBM Spokane Research Center. In particular we wish to acknowledge the generous support provided by the Technical Project Officer, Mr. John Franklin and by his associates, Mr. Keith Weverstad, Mr. Wayne Howie, and Mr. Roger McVey. Finally, the authors acknowledge the important contributions of colleagues at Arthur D. Little, Inc., particularly Dr. James Oberholtzer, who supervised data transcription, Ms. Janet Wagner, who handled data reduction and transcription, and performed computer analyses, and Mrs. Joanne Piandes, who typed all reports and acted as communications center throughout the program.

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I. ABSTRACT

This report describes an experimental program which we conducted on behalf of the U. S. Bureau of Mines, to select from currently available materials two novel systems of construction for air-restraining bulkheads to be used in control of radon-polluted air in underground uranium mines. The program included both laboratory and field tests, the latter conducted in a portion of an operating mine owned and operated by Union Carbide Corporation at LaSal, Utah. The test site was a worked-out, double entry stope having a volume of about 2000 cubic meters, and was located immediately adjacent to an exhaust airway. The bulkheads were constructed of 15 cm x 15 cm timber uprights, 5 cm x 15 cm horizontal members supporting a close-fitted 13 mm plywood curtain-wall, which was covered with a low-permeability membrane to seal in the radon-polluted air.

The two membrane materials selected for testing were chosen from a list of twenty-two potentially acceptable candidates using criteria such as strength, flammability, ease of application, adhesion, radon permeability, and elasticity. Thirteen of the candidates were tested in our laboratories for adhesion to plywood and to both wet and dry concrete (simulating wet and dry mine rock surfaces), and for their general physical properties, including radon permeability. The final selections made by the Technical Project Officer, and based on our recommendation, were a pre-formed ethylene propylene diene monomeric rubber (EPDM) membrane 1.12 mm thick, normally used as a roof sealant in industrial construction, and available from Carlisle Tire and Rubber Co., Division of Carlisle Corp., Carlisle, PA, and Aquafas 48-00, a water-based mastic used in a wide variety of commercial applications and available from H. B. Fuller Co., Foster Products Division, Spring House, PA. The EPDM membrane was applied as a single sheet, laminated (dry) between two layers of plywood, and the Aquafas was applied both by troweling and spraying onto a plywood surface.

In the field test, radon concentrations were continuously measured before, after, and in the trapped air behind each bulkhead. Temperature, pressure, and velocity of the air in the adjacent airway were also measured and recorded continuously. Radon fluxes at the rock/air interface and through the bulkheads themselves were measured manually on a frequent basis. All continuously acquired raw data were recorded automatically on two USBM Data Aquisition Systems (DAS), and the raw data were converted into engineering units and recorded on magnetic disks by a specially programmed microcomputer that was interfaced with the DAS's.

Relatively clean (i.e. low radon concentration) air was pumped into a point near the face of one test bulkhead from a location 170 meters away through vent bag. Several air curtains and two air-restraining bulkheads were erected in passageways adjacent to the test area in an effort to control both velocity and radon concentration of the air flowing past the bulkhead faces. An average concentration of

approximately 500 pCi/liter at a flow of 550 m^3/minute was attained as the background concentration against which leakage through the bulkheads was measured.

The entire field test period extended from October, 1981 to March, 1982, a total of six months, and was subdivided into seven successive time periods:

1) site preparation

2) background measurements prior to bulkhead construction

3) passive restraint, with bulkheads in place and totally sealed

4) open bleeder period of natural convection ventilation in and out of the bulkheaded area through a 10 cm (diameter) opening, with connecting tubing leading into an exhaust airway

5) open bleeder period, having forced exhaust through a 10 cm opening using a servo-controlled fan

6) charcoal trapping period, using the servo-controlled fan to exhaust air through the charcoal traps, to test the effectiveness of such traps in removal of radon from the exhausted air

7) site decommissioning

Each of the two systems tested, one incorporating the pre-formed EPDM-rubber membrane and the other utilizing Aquafas 48-00, was assessed for effectiveness in controlling radon-polluted air by observing the change in the radon concentration in the ventilation air flowing continuously over the surface of each bulkhead. The sensitivity of the observed measurements was limited by the volume flow-rate of the ventilation air and the radon concentration in that air. The data would indicate that the observed increments in radon concentration in the ventilation air moving across bulkheads B-1 and B-2 were essentially zero within the limits of sensitivity of the measurements.

Data from radon flux measurement taken both on the sealed ribs adjacent to the bulkheads and on the bulkheads themselves did not differ significantly from blank data.

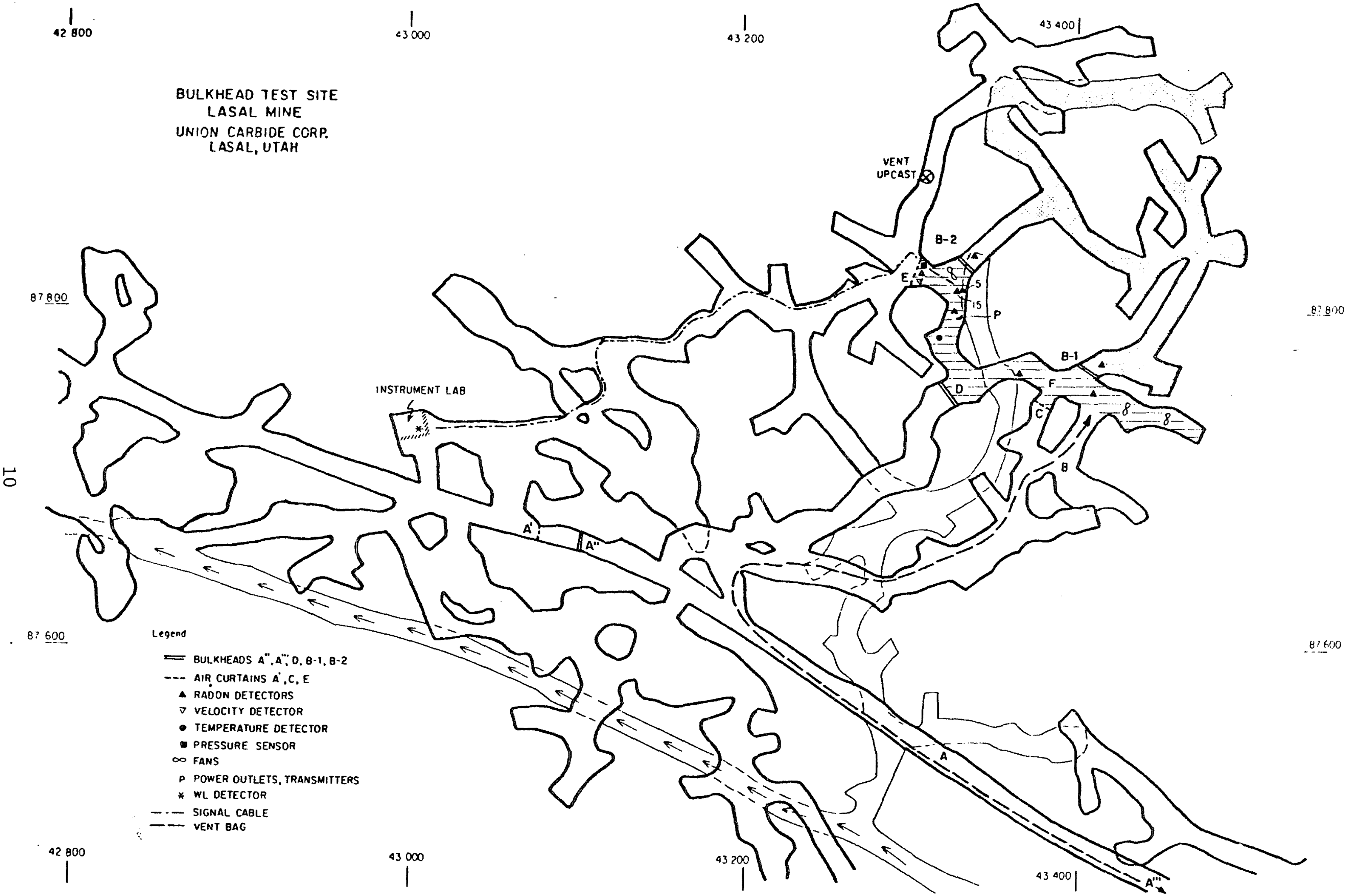
BULKHEAD TEST SITE
LASAL MINE
UNION CARBIDE CORP.
LASAL, UTAH
42 800
43 000
43 200
43 400
87 800
87 600
VENT
UPCAST
B-2
E
P
B-1
F
D
C
B
INSTRUMENT LAB
A'
A''
A
A'''
Legend
BULKHEADS A'', A''', D, B-1, B-2
AIR CURTAINS A', C, E
RADON DETECTORS
VELOCITY DETECTOR
TEMPERATURE DETECTOR
PRESSURE SENSOR
FANS
POWER OUTLETS, TRANSMITTERS
WL DETECTOR
SIGNAL CABLE
VENT BAG

FIGURE 1

II. INTRODUCTION

Bulkheads have long been constructed as air-restraining and air pollution control devices in underground uranium mines to effect a reduction in the costs associated with the need to limit radon and radon daughter levels in mine air. Unfortunately, very few data demonstrating the effectiveness of bulkheads have ever been made public.

Bulkheads must be strong enough to withstand considerable impact (accidental contact by mining vehicles), ground movement and transient air pressures due to blasting in their vicinity, and be resilient enough to maintain an air-tight seal. Radon concentrations in air in a sealed-off area will quickly approach those existing within the surrounding rock and can easily be in excess of 30,000 pCi/l. Since all the air in sealed-off workings is free to move quite rapidly in response to small pressure gradients, bulkhead leaks that permit escape of the trapped air at only relatively slow rates (i.e., a few cfm) can easily increase radon concentrations and WL's* in air of adjacent workings to unacceptable levels over periods of hours or even a few days. Chronic effects have often been experienced in periods of repeatedly cycling barometric pressures, and in situations where large reservoirs of trapped (and highly radon-polluted) air communicate through leaky bulkheads and other routes with relatively small volumes of ventilation air.

Some relief of positive air pressure conditions in sealed-off mine workings can be achieved by the simple expedient of opening a low-resistance air passage or "bleeder" between the bulkheaded area and a convenient exhaust airway. Because a pressure bleeder can be only partially effective in overcoming an environmentally (or artificially) induced pressure differential, however, imperfectly sealed bulkheads may still leak to some extent under the influence of the remaining differential.

An alternative that has been used, and which may be the only practical solution in situations where the bulkheaded area is penetrated by many small in-leak airways such as may be produced by long-holes that connect with the surface or with other parts of the mine, is to continuously exhaust moderate volumes of air from the area to a suitable exhaust airway. This approach, which is actually a limited type of dilution ventilation, serves to diminish the likelihood of uncontrolled

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*Although the units "WL" and "WLM" are undoubtedly familiar to readers of this report, it may be well to recall that the Working Level (WL) is a concentration of any combination of the short-lived daughters of ^{222}Rn in 1.0 liter of air sufficient to result in the emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy from radioactive decay. The Working Level Month (WLM) is a unit of radiation exposure obtained from working in (and inhaling) air containing 1 WL of radon daughters for a period of one month (173 hours).

escape of the radon-rich air into supply airways, and also reduces the concentration of radon in the bulkheaded area, thus diminishing the adverse impact of any uncontrolled leaks on the cleanliness of the supply air. The cost of operating such a limited ventilation system for inactive areas may be somewhat higher than that of achieving a near-perfect passive containment system, but practical circumstances may not allow a choice.

Safe disposal of the exhaust air from a sealed-off inactive area can present some problems, expecially if the polluted air cannot be exhausted directly into an isolated waste-airway. Large diameter flexible fabric or plastic vent-tubing is not considered safe for conduct of polluted exhaust air through occupied portions of the mine, since this kind of air conduit is best operated under positive pressure, which exposes the system to the possibility of leaks, and thus to contamination of the air around it. To operate an exhaust vent-tube under negative pressure, the tube must be made of a rigid material such as metal, fiberglass-reinforced plastic, or wire-wound plastic. Rigid air conduits are not impractical, but neither are they widely used in underground mines, largely because of their higher cost and greater susceptibility to damage than flexible tubing.

If no satisfactory means can be found for conducting the radon-polluted air safely out of the mine, or if there exists a need to minimize additional quantities of radon vented to the surface, it has been suggested that charcoal filtering be used to remove radon from waste air. It has been shown that the amount of charcoal needed would be determined principally by the volume-rate of air to be treated (1) and the desired reduction of radon concentration in the exhaust air.

In-house efforts by USBM/SRC (2) have shown that areas can be effectively sealed with bulkheads constructed of expanded metal lath sealed with a rigid inorganic (and therefore non-combustible) cement, and equipped with bleeder pipes. The program whose results are presented here was designed to identify the best currently available materials that could be used in bulkheads constructed for radon control, to determine their cost, relative effectiveness, ease of handling, safety aspects, and to test the performance of two of the best candidates in an active underground uranium mine. Performance was tested both with

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(1) Lindsay, D. B. and others. Advanced Techniques for Radon Gas Removal. Arthur D. Little, Inc. Report - USBM Contract Report H023002. 1975, 170 pp.

(2) Franklin, J. C., C. S. Musulin, D. W. Thebeau, Research on Bulkheads for Radon Control in Mines. Proceedings of the Second Conference in Uranium Mining Technology Reno, Nevada, November 13-17, 1978, 11 pp.

and without a powered exhaust system. The feasibility of using a charcoal trap as a radon adsorbent to minimize pollution of waste air by the exhaust from the bulkheaded area was also investigated.

III. SCOPE OF WORK

This program was designed to accomplish two objectives:

1. to determine, from a study of currently available products, two types of bulkhead-sealing materials which, when used in conjunction with conventionally acceptable framing methods, would produce superior systems for confining radon-polluted air in inactive areas of underground uranium mines, and

2. to measure leakage of radon through the two experimental bulkheads and to test the effectiveness of a charcoal trap for purging radon from air exhausted through a fan-powered bleeder pipe.

These objectives were divided into two phases: Phase I included selection of the site, and material evaluation with subsequent selection of the two materials to be tested; Phase II included all field work.

The requirements for this program were specified by USBM in the original contract Statement of Work. Some modifications in the Scope of Work were made during the course of the contract, most of which were designed to enhance the yield of useful data from the program. A few minor deletions were made to allow some operations to be reduced or eliminated if their value was agreed to be slight.

A Modifications

Principal modifications in the scope were as follows:

1. The Technical Project Officer visited our Cambridge laboratories to meet the personnel who would be involved in the program and to discuss implementation of the work plan. It was agreed that the planned training session for our personnel which was to take place in Spokane, Washington, during the first phase of the work would be omitted, since the people to be involved in the field work already had a working familiarity with the equipment and procedures to be used.

2. It was also agreed that certain modifications in the work schedule proposed initially by the Bureau could be introduced with benefits in saving of time and improvements of results. One such modification would be in the use of two similar test sites to permit testing of the two bulkheads simultaneously, rather than sequentially.

3. The requirement to rank materials on the basis of cost per 930 cm^2 at 19 mm thickness was modified to allow use of effective thickness, which in many instances differed considerably from 19 mm.

4. Design of a suitable charcoal trap for use in the final period of the field test was agreed to be a task that could be deferred until such time as we could determine what volume flow rate of air had to be withdrawn from behind the bulkhead in order to maintain a favorable pressure gradient across it.

5. Substitution of a 100 mm aluminum pipe for the 150 mm plastic pipe as stated in the Statement of Work was also agreed to be suitable, and allowed the use of 100 mm flexible dryer tubing (overcoated with Aquafas 48-00, a mastic sealant) to vent bulkheaded air into an exhaust airway.

6. Monitoring of the radon concentration immediately behind each bulkhead was substituted for monitoring the radon concentration of the air in the bleeder pipe.

7. A Working Level monitor was installed inside the underground room used as workshop and data acquisition center since grab samples had shown this area to be high (above 1 WL at times) in radon.

8. By agreement with the TPO and mine management, all equipment was returned to the surface, packaged, and stored for USBM pickup rather than shipping to USBM/SRC, since a new series of tests were to be started in the same general area. This change resulted in a monetary savings and insured proper care of Bureau equipment during transporting.

9. The two experimental bulkheads and all air direction and control bulkheads, as well as the drums containing charcoal, were left in place as per the agreement signed by Union Carbide area supervisors and the Arthur D. Little, Inc., representative (see copy of agreement, Appendix A-2).

10. All photographs were color slides to improve effectiveness of presentations.

IV. PHASE ONE - SELECTION AND TESTING OF CANDIDATE BULKHEAD MATERIALS

A. Initial Selection

The evaluation of candidate sealant materials for use on radon-control bulkheads was conducted in our laboratories and led to the development of quantitative data and qualitative information from which the Bureau's Technical Project Officer was able to choose two preferred materials for final field testing. The evaluation process began with a reasonably complete selection of representative types of materials, based on our knowledge of the characteristics, costs, and commercial availability of such materials. Our evaluation was based on a combination of data provided by manufacturers and obtained from trade literature and other sources, and was augmented by limited testing in our laboratories. The data developed by this process were representative of specific commercial products at the time that this search was conducted. However, it must be remembered that manufacturers are free to make changes in material composition of their products that might significantly affect test results. The test results were applicable only to the task of selecting two candidate systems for testing in the underground mine. No endorsement of any material with respect to safety or efficacy has been stated or implied in our reports.

We obtained and reported relevant data on the composition of various materials with regard to potentially toxic components, but our observations were not intended to guarantee the complete absence of any and all toxic (expecially suspected carcinogenic) materials, either from the initial composition of a product or from its combustion products. The "threshold value limit" referred to in the Statement of Work of the subject request was taken to be the "OSHA Standard" for permissible concentration of various substances in workplace air. The OSHA Standards are generally intended for control of environments for continuous human exposure, as distinguished from momentary or occasional exposure. Some Standards are so-called "ceiling" limits, which are not to be exceeded at any time, even momentarily, but most of the values were taken as eight-hour time-weighted averages, on the assumption that those averages represent continuous conditions. The concentrations thus obtained will be influenced by the ventilation rates, i.e., the air turn-over rate, in the workplace, making the establishment of OSHA Standards for bulkhead materials strongly dependent on ventilation conditions at the face of the bulkhead.

Because some materials of construction might emit toxic or flammable fumes in hazardous quantities during application as, for example, solvent fumes that might be emitted from an organic surface-sealant while it was being applied, drying and/or curing, consideration was given to possible hazards of this kind. Presumably, once the bulkhead was finished, no further evolution of toxic or flammable vapors occurred. Our study included acquiring information on potential occupational hazards associated with application of various candidate materials, as well as information on health and safety hazards they might present once they were in place. This information was provided to the Technical Project Officer for use in the selection of the preferred systems for evaluation. We did not attempt to certify the safety or efficacy of any particular product or combination of materials or, in general, to verify the accuracy of data from other sources unless existing data were obviously unsatisfactory or incomplete.

In addition to evaluating the testing materials in our laboratories, we consulted a number of mine engineers regarding their experiences with bulkhead construction and operation and their current construction preferences and general observations. Unfortunately, no reliable data on radon control was available from any of them.

Early in the program, we conducted several sessions with members of our own professional staff who had expertise in a number of material and construction areas. In these sessions, we generated ideas for possible bulkhead constructions and materials to be used in those constructions.

In these discussions, we focused on the fact that there are essentially three functional parts to a bulkhead and that different properties are needed in the three parts. The primary part of the bulkhead is the basic structure that fills most of the opening. This can be a relatively rigid structure which provides primary resistance to mechanical abuse, blasting shocks, pressure differentials, etc. It may be a continuous non-porous membrane itself or it may support such a membrane which might be attached to this primary structure or sprayed onto it. The important characteristics of this part of the bulkhead are: 1) structural strength which is maintained for an extended period in the mine operating environment; and 2) membrane continuity, that is, it must not crack or develop holes or leaks in the mine operating environment.

The second part of the bulkhead is the portion that forms the seal between the primary structure and the rock wall of the opening. This part is relatively narrow and is supported by the primary structure, so that limited structural strength is required, but this portion must provide a positive seal which is maintained through blasting shock waves, rock movement, running water, and other adverse conditions of the mine operating environment.

The third part of the bulkhead is the surface sealing of the rock for a distance of approximately one meter from the plane of the bulkhead in order to minimize migration of radon around the bulkhead through the rock. This seal must be of a material that will adhere to and seal the surface of the rock even if it is damp. It must maintain positive sealing of the rock surface through normal movement of the rock, blasting, water influx, and other conditions to be expected in the mines.

Although the three parts of the bulkhead serve different functions, that does not necessarily mean that different materials must be used for the different parts. For instance, polyurethane foam has been used as a membrane to cover all three parts of the bulkhead and is reported to be reasonably satisfactory, except for its flammability.

We developed lists of types of materials that might prove useful in bulkheads and we contacted a number of manufacturers of those types of products to obtain data on properties and cost and samples for laboratory evaluation.

These classes of materials included:

- Board and lath products that might be attached to timbers to form the primary structure.
- Penetrating sealants that might be applied to the rock to penetrate cracks and fissures and seal the rock surface.
- Pre-formed membranes that might be bonded in place such as rubber sheeting, coated fabrics, and roof membranes.
- Spray-in-place membranes such as mastics, and reinforced cement products.

The total list of materials considered as potential bulkhead sealants is as follows:

PRODUCT	COMPANY	DESCRIPTION
1. *Monolar II 60-56	Foster/HB Fuller	Hypalon-based vapor barrier coating, 30% total solids in solvent.
2. *CI Mastic 60-26	Foster/HB Fuller	Asphaltic-based cutback coating, 64% total solids in solvent.
3. *Aquafas 48-00	Foster/HB Fuller	Water-based mastic, 61% total solids.
4. Chemical Grout LX 463	3M	Urethane-based solid stabilizer.
5. Sewer Grout CR202	3M	Urethane-based gel/foam.
6. *Scotchgrip 5230	3M	Single-component urethane-based.
7. Coating/Caulk 5200	3M	Gun-grade version of 5230.
8. *Quaker Koat	Quaker State	Water based emulsion of asphalt and special fillers, 53% total solids.

9.	Tremproof	Tremco	Single-component bitumen-modified moisture-curing polyurethane.
10.	*Rezklad Machinery Grout	Atlas	100% solids epoxy resin-based grout. Three part system of resin, hardener, filler with working life of 30 minutes at 76°F.
11.	*Stoppit	Michael Walters	Asbestos-filled sodium silicate.
12.	*LM 3000	WR Grace	Two-component, 100% solids elastomeric cold-applied mastic membrane.
13.	Bituthene 3000	WR Grace	60-mil rubberized asphalt bonded to polyethylene film.
14.	*Bituthene 3100	WR Grace	60-mil tackier grade of Bituthene 3000.
15.	Butyl Roof Membrane	Carlisle Rubber	30-mil butyl, nylon-reinforced membrane.
16.	EPDM+ Roof Membrane	Carlisle Rubber	45-mil EPDM nylon-reinforced membrane.
17.	*Liquiseal	Carlisle Rubber	Two-component polyurethane roofing membrane.
18.	Phily Clad 5020	Philadelphia Resin	Trowelable epoxy floor surfacer.
19.	Bituplastic No. 33	Koppers	Mineral polymer-modified coal tar emulsion, possibly fibrated form.
20.	SIROC Chemical Grout	Diamond Shamrock	Glyoxal silicate soil-stabilizer grout.
21	*Mine Shield	American Energy Products	Inorganic cement mine-stopping.
22.	*Miracote	Frontier, Inc.	Latex-modified cement, water-based.

+EPDM = ethylene propylene diene monomer
*Selected for further testing

NOTE that sample nos. 13, 14, 15, and 16 were pre-formed membranes supplied in sheet form. Except for Bituthene 3100, which had a moderately tacky surface, all of these would have required an adhesive coating for application to plywood. None of them would have been suitable for use on irregular rock or concrete. Sample No. 11, Stoppit, contained asbestos, and was therefore not acceptable. All the organic solvent-based coatings were flammable except for No. 1, Monolar II 60-56.

B. Screening

1. Initial Testing

On the basis of manufacturers' product literature and examination of samples, the thirteen products marked with an asterisk (*) were selected as candidates, and were tested in our laboratory for adhesion to plywood and to wet and dry concrete and for general physical properties. In addition, two rubber sheet materials similar to 15 and 16 but without reinforcement were selected as candidates. For some of the materials where flammability was of particular concern, we also ran vertical small-strip flammability tests. In this test, a 6 mm x 38 mm strip of the coating material was removed from the substrate. The strip was suspended vertically, and the lower end ignited with a match. Ignition and vertical flame spread were observed.

Information obtained in our tests and from the manufacturer's literature on each of the candidate materials is summarized in the following sections.

1. Monolar II 60-56

In our tests, this material showed excellent adhesion to plywood and dry concrete, and formed a dry film with good strength and elongation characteristics. In small flame ignition tests, a strip of the film burned when exposed to flame but self-extinguished following removal of the outside heat source.

The manufacturer's literature indicates that it contains solvents with a flash point of 38°C. It also states that the dry film has a surface flame spread of 20 when tested on cement asbestos board by the ASTM E84 method.

2. CI Mastic 60-26

This product also showed excellent adhesion to plywood and wet and dry concrete; however, the film was rather weak. According to manufacturer's literature it contains solvent and has a flash point of 43°C; also, the flame spread when tested on cement asbestos board by the ASTM E162 method is stated to be 145.

3. Aquafas 48-00

This material showed excellent adhesion on wet concrete and good to fair adhesion on dry plywood and dry concrete. It appeared that a dampening of the surface prior to application would improve the adhesion on the dry materials. The dry film had good strength and fair to good elongation characteristics. In a small-strip ignition test performed at Arthur D. Little, the material did not burn. Manufacturer's literature on this material states that it is a water-based mastic and has no flash point below the boiling point.

4. Quaker Koat

This material had excellent adhesion to plywood and wet and dry concrete. The film had fair to good strength but low elongation which resulted in cracking on bending of the specimen. In a small-strip ignition test, it burned moderately with flaming droplets of molten material falling from the specimen. The data sheets indicate that, in the wet form, it has a flash point of 71°C, even though it is a water emulsion.

5. Tremproof 60

This material had excellent adhesion to plywood and wet and dry concrete. The dry film had good strength and excellent elongation characteristics, and showed moderate burning in a small-strip ignition test. According to the literature, it has a flash point of 57°C in the wet form.

6. Rezklad Grout

This material showed excellent adhesion to plywood and wet and dry concrete. It is a strong but rigid material in the cured form. The concern that it would not survive blasting shocks intact made it appear unsuitable for the bulkhead application.

7. Stoppit

This material showed excellent adhesion to plywood and wet and dry concrete. It is completely inorganic. The dry film is brittle and also contains asbestos; therefore, it was rejected.

8. LM3000

This liquid membrane material showed excellent adhesion to plywood, poor-to-fair adhesion to dry concrete, and fair adhesion to wet concrete. The cured film had fair-to-good strength and good elongation. Small-scale ignition tests indicated that a strip of the material would ignite and burn moderately. According to data sheets, it is a two-component product which contains no solvent and therefore presumably has a high flash point.

9. Bituthene 3100

This pre-formed membrane had fair-to-poor adhesion to plywood and wet and dry concrete. The film had good strength and fair-to-good elongation characteristics. On a small-strip ignition test it ignited and burned moderately.

10. Liquiseal

This material showed excellent adhesion to plywood and wet and dry concrete. The cured film was strong and had good elongation. A small strip ignited and burned moderately. The data sheet indicates this is a two-component material with no solvent, and a flash point of over 149°C.

11. Scotch Grip 5230

This material had excellent adhesion to plywood and wet and dry concrete. The cured film was very strong and rubbery. A small strip ignited and burned moderately. According to 3M, it contains no solvent but it does contain toluene diisocyanate and should be used only in well-ventilated areas.

12. Mine Shield

This material had poor adhesion to plywood and fair adhesion to wet and dry concrete. It is a hard, brittle material which would be likely to have some porosity and might crack under stress. It, therefore, did not appear to be useful for our purposes.

13. Miracote

This material had excellent adhesion to plywood and wet and dry concrete. It had good strength but limited elongation and cracked on bending. It also had to be applied in several coats, with time required between coats to allow partial drying of the previous application. The low elongation and multiple coat application made this material appear unsuitable for our purposes.

14. Butyl Rubber Membrane

This was a dry membrane that would have to be bonded with an adhesive; it had not inherent adhesion. It was originally obtained with nylon fabric reinforcement. In this form it had low elongation. The unreinforced form had good strength and elongation and appeared more suitable as a membrane for a bulkhead. A small strip exposed to flames ignited and burned moderately.

15. EPDM Membrane

Like the butyl membrane, this material was not tested for adhesion; it would have to be bonded in place with a separate adhesive or be mechanically fastened. It had excellent strength but only fair elongation in the form of a nylon scrim-reinforced membrane. The unreinforced form was tested and found to have better strength than the butyl membrane, as well as good elongation. In a small-strip test, it ignited and burned slowly to moderately.

2. Bulkhead Design Philosophy

We used the premise that the basic bulkhead structure would consist of a timber or metal stud barrier covered with expanded metal lath or any of several sheet products such as plywood, wafer board, hardboard, or waterproof gypsum board.

Our preference was to find a single flexible, durable, sealant material that could be sprayed onto the basic structure, the joint between the basic structure and the rock, and the adjacent rock to form a continuous seal and radon barrier.

We did not, however, abandon other (though less idealistic) approaches. We realized that in addition to the concept of a basic structure covered by a sealing membrane, other auxiliary materials might be required. These might include a fabric to reinforce the membrane to form a strong flexible bond between the primary structure and the wall. For wet rock wall, a special primer or sealant might be necessary to gel the water and fill the cracks so that a membrane could be sprayed in place. For extremely rough rock, a filler to provide a smoother surface for the membrane might be necessary. Polyurethane foam would be useful for this purpose, but it could not be left exposed. It would have to be covered with a flame retardant coating.

As possible substitutes for polyurethane foam, we investigated organic foams reported to be less flammable than polyurethane such as phenolic and urea formaldehyde. These foams were not considered to be satisfactory membranes for our purposes, however, because they have, or develop with time, an open cell structure that allows gases to readily pass through them. They might, however, be useful as gap fillers over which a flexible membrane could be applied. We did not find any non-urethane foams that appeared to have sufficient potential to warrant evaluation. We therefore decided to use the urethane foam as necessary for gap filling and sealing and to cover it to eliminate any flammability problems.

3. Initial Cost Estimates

We anticipated during the materials selection process that one test bulkhead would be of low cost conventional construction such as

Mine Shield sprayed onto metal lath. The second would utilize somewhat more costly materials which would represent a more flexible and potentially more effective radon barrier.

Based on this approach and the previously outlined design philosophy, we developed some initial cost estimates for a 460 cm by 300 cm bulkhead. These estimates were prepared in the form of separate costs for several basic supporting structures, a polyurethane foam peripheral sealant and several different sealant/membrane materials. Those costs were prepared in this way so that we could estimate bulkhead costs using various combinations of components. In making these estimates, we utilized available information from mine engineers as well as materials suppliers. We fully realized at the time that these costs would not represent actual installed costs which would vary significantly from mine to mine, depending on conditions. Our goal in developing these initial costs was to put all systems on an equal basis so that we could have some indication of the relative costs of the various systems.

It also became clear at this point in the study that comparison of the various bulkhead constructions on the basis of equal thickness would serve no useful purpose. Costs were developed, therefore, on the basis of a thickness of each material that would provide effective sealing based on the manufacturer's recommendations. As a final step in making these initial cost estimates, we combined costs of the various components to obtain relative costs of conventional Mine Shield systems and low cost and high cost, high performance experimental systems. All of the initial costs are contained in Table 1.

4. Radon Permeation of Selected Materials

As a final step in generation of data that would be useful in making the final selection of materials for the test bulkheads, we ran radon permeation tests on a number of candidate materials. The radon permeation rates were determined using a symmetrically-constructed scintillation counting chamber (see Figure 2), which eliminated the need for absolute calibration. Two cylindrical chambers, each with a coating of ZnS on the inside bottom surface, were sealed together by beeswax with the test piece acting as a divider between the two chambers. Two filter-topped vials containing uranium ore were fixed to the inside of one chamber while two empty filter-topped vials were fixed to the inside of the other chamber, again retaining symmetry. The rate of growth of radon in the test chamber was then monitored using a photomultiplier/counter system (Ludlum Model 182). Knowing this rate, and the equilibrium concentration in the ore-containing chamber, a permeability could be calculated. There was some question about the accuracy of the absolute values obtained in these tests, but we believe that the <u>relative</u> values are correct and provided some basis for selection between materials. It should be emphasized that these values did not take into account the thickness of the membrane specimen, and the specimens were not all of the same thickness. They were made up in the thickness recommended by

TABLE 1

On the basis of a typical 460 cm by 300 cm bulkhead, the costs for materials and labor were estimated for a variety of supporting structures, peripheral sealants, bulkhead facing sealants, and for several suggested test-combinations.* Labor costs were based on an estimate of $15/hour.

	Estimated Costs ($)		
	Materials	+ Labor	= Installed Cost
1. Supporting Structure‡			
1. 10cm x 10cm + 5cm x 20cm planking	82	105	187
2. 10cm x 10cm + 13 mm plywood	54	90	144
3. 10cm x 10cm + 13 mm Homosote	43	90	133
4. 10cm x 10cm + 11 mm wafer-board	51	90	141
5. 10cm x 10cm + 16 mm gypsum board	67	90	157
6. 10cm x 10cm + metal lath	57	100	157
7. 10cm x 10cm + metal lath + polyethylene film	61	110	171
(10cm x 10cm's spread 60 cm apart)			
2. Peripheral Sealant			
1. Rigipak 180 (PU foam)	131	3	134
3. Bulkhead-Facing Sealants			
1. Monolar 60-56 @ 45 mils‡	387	8	395
2. CI Mastic 60-26 @ 60 mils	122	8	130
3. Aquafas 48-00 @ 60 mils	172	8	180
4. Quaker Koat @ 63 mils	75	8	83
5. Tremproof 60 @ 60 mils (trowel)	148	15	163
6. Rezklad Grout @ 60 mils (trowel)	145	15	160
7. Stoppit @ 60 mils (trowel)	24	15	39
8. LM3000 @ 90 mils	315	8	323
9. Bituthene 3100 @ 60 mils	175	8	183
10. Liquiseal @ 55 mils	155	8	163
11. Scotchgrip 5230 @ 60 mils (trowel)	458	15	473
12. Mine Shield @ 13 mm	192	15	207
13. Miracote @ 90 mils (multi-pass)	225	15	240
14. Butyl membrane @ 30 mils	210	8	218 } = 318
+ adhesive	92	8	100 }
15. EPDM Membrane @ 45 mils	280	8	288 } = 388
+ adhesive	92	8	100 }

*Costs are at effective thickness as listed above in #3.
‡Sealant thicknesses are measured in mils (1 mil = 0.001 inch)

TABLE 1 (continued)

	Estimated Costs ($)		
	Materials +	Labor =	Installed Cost
4. Recommended Combinations			
a. Conventional Systems			
1. 10cm x 10cm + 5cm x 20cm planking + Mine Shield	274	120	394
2. 10cm x 10cm metal lath + Mine Shield	249	115	364
3. System 1 + peripheral sealant	405	123	528
b. Experimental Systems			
1. Lowest Cost			
10cm x 10cm + 13mm Homosote + peripheral seal + Tremproof 60 or Liquiseal	322	108	430
2. High Performance			
10cm x 10cm + 13mm plywood + peripheral seal + Scotchgrip 5230	643	108	751
or			
with Monolar 60-56 (for flame resistance)	572	101	673

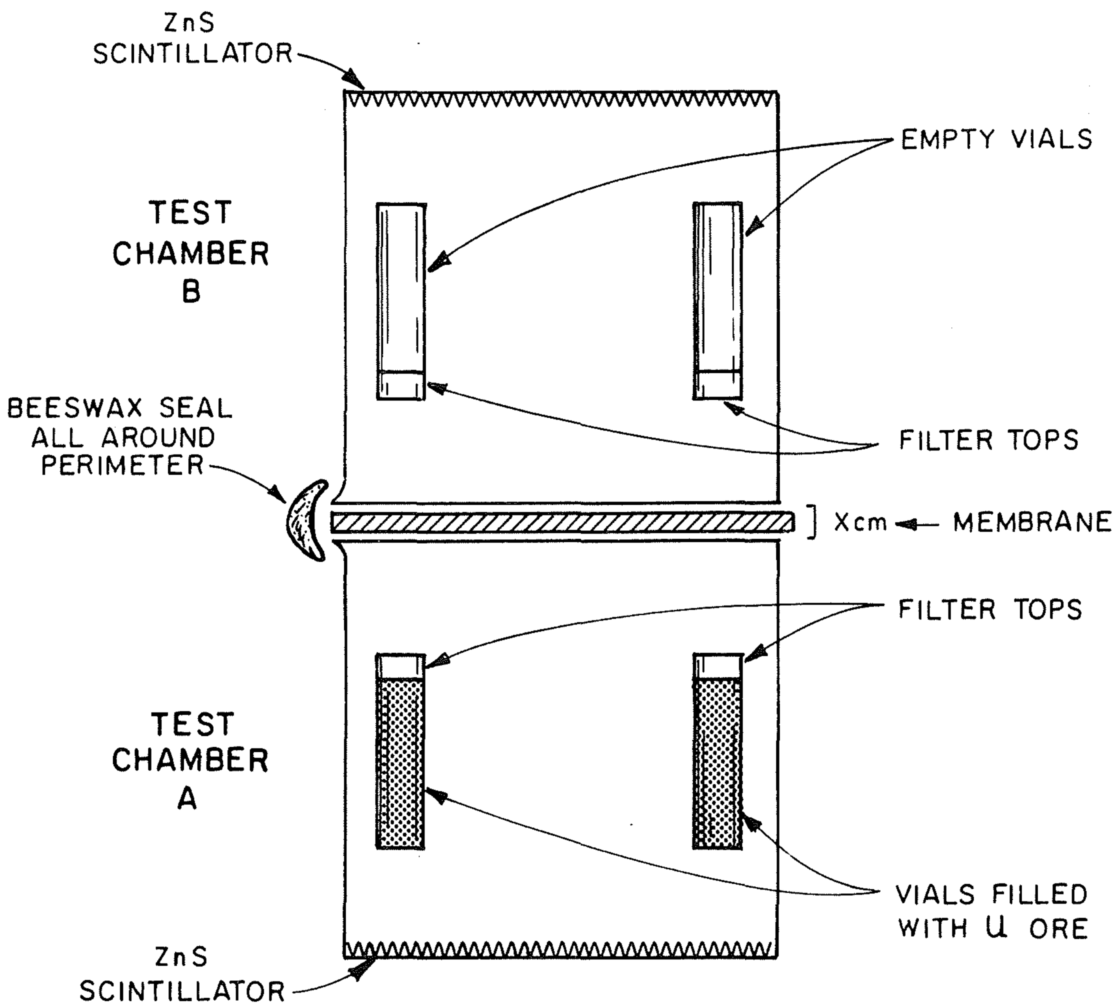


FIGURE 2 Radon Permeability Test Apparatus

the manufacturer of each, however, so that direct comparison of the test data did provide a satisfactory basis for differentiation.

The rigid specimens, even though they were generally thicker than the resilient specimens, tended to show high diffusion values, presumably due to porosity or cracking in the specimens. Even before these results were obtained, on the basis of other work we had concluded that a resilient, elastomeric membrane material would be essential in order to maintain barrier continuity through blasting shock, earth movement, etc. The ability of a membrane to maintain its integrity and not develop cracks is probably more important in its performance as a sealing bulkhead than its actual radon permeability.

A summary of data on the various sealant/membrane materials is contained in Table 2.

A summary of information and data on the materials evaluated for radon permeability, plus butyl and EPDM pre-formed membranes is given in Table 3.

The two systems suggested, and accepted, for evaluation were to be constructed as follows:

Both basic structures would be 15 cm x 15 cm timber uprights with 5 cm x 15 cm horizontal crosspieces. 13 cm plywood would be cut to follow the contours of the rock, and form a frame for the applied membrane. A bead of foam-in-place polyurethane (Mine Safety Appliance's Rigipak) would be used to interface the rock and wood surfaces and effect a reasonably flexible seal.

One membrane would be Aquafas 48-00, sprayed or troweled on the plywood and polyurethane to form a coating approximately 1.5 mm thick.

The other membrane would be EPDM rubber sheeting applied as a single sheet 1.1 mm thick, and overlayed with 6 mm plywood to add rigidity and reduce flammability. The edges of the membrane would be sealed to the rock surfaces using horizontal and vertical grade sealants previously developed to aid in other types of applications.

Each bulkhead would cost $600-800, most of which would be attributable to labor involved in fitting the plywood to the rock shape.

These two systems appeared to best meet the requirements of presenting a minimum hazard in the mine during and after construction, required a minimum of mechanical equipment for their construction, and were relatively low in cost.

C. Site Selection

The current low demand for processed uranium ore (yellow cake) had forced many companies involved in mining and milling uranium to curtail

TABLE 2

SEALANT/MEMBRANE MATERIALS DATA SUMMARY

	Product	ADHESION			Cured Surface	Cohesive Strength
		Plywood	Wet Concrete	Dry Concrete		
1.	Monolar II 60-56	Excellent	Excellent	Excellent	Non-tacky	Moderate; rubbery
2.	CI Mastic 60-26	Excellent	Excellent	Excellent	Non-tacky	Weak; mushy
3.	Aquafas 48-00	Good	Excellent	Fair	Non-tacky	Moderate; resilient
4.	Quaker Koat	Excellent	Excellent	Excellent	Non-tacky	Poor resilience; cracks on bending
5.	Tremproof 60	Excellent	Excellent	Excellent	Slightly tacky	Tough; rubbery
6.	Rezklad Grout	Excellent	Excellent	Excellent	Non-tacky	Strong; rigid
7.	Stoppit	Excellent	Excellent	Excellent	Non-tacky	Brittle
8.	LM 3000	Excellent	Moderate	Fair	Non-tacky	Moderate; rubbery
9.	Bituthene 3100	Fair	Poor	Fair	Non-tacky	Fair; rubbery
10.	Liquiseal	Excellent	Excellent	Excellent	Non-tacky	Strong; rubbery
11.	Scotch Grip 5230	Excellent	Excellent	Excellent	Non-tacky	Strong; rubbery
12.	Mine Shield	Poor	Moderate	Moderate	Non-tacky	Hard; brittle
13.	Miracote	Excellent	Excellent	Excellent	Non-tacky	Poor resilience; cracks on bending

TABLE 3

SUMMARY OF DATA ON BULKHEAD MEMBRANE CANDIDATE MATERIALS

		Properties				Flammability			
					Radon		Dry		
Product	Adhesion	Strength	Elongation	Radon Permeability*		Wet	Spread	Ignition	Comments
1. Monolar II 60-56	Excellent	Good	Good	2.2×10^{-7}		High	20	Low	Flammability?
2. CI Mastic 60-26	Excellent	Poor	Fair	3.8×10^{-5}		High	145	High	Too weak
3. Aquafas 48-00	Good	Good	Fair	3.6×10^{-7}		None	None	None	Good candidate
4. Quaker Coat	Excellent	Fair	Poor	2.5×10^{-6}		Medium	NA	High	Too weak
5. Tremproof 60	Excellent	Excellent	Good	6.9×10^{-8}		Medium	NA	Medium	Flammability?
6. Rezklad Grout	Excellent	Good	Poor	1.3×10^{-5}		Low	NA	NA	Brittle
7. Stoppit	Excellent	Good	Poor	3.1×10^{-5}		None	None	NA	Brittle, contains asbestos
8. LM 3000	Good	Good	Good	2.5×10^{-5}		Low	NA	Medium	Flammability?
9. Bituthene 3100	Fair	Good	Good	1.7×10^{-5}		None	NA	High	Flammability?
10. Liquiseal	Excellent	Excellent	Good	1.0×10^{-4}		Low	NA	Medium	Flammability?
11. Scotch Grip 5230	Excellent	Excellent	Good	8.5×10^{-6}		Low	NA	Medium	Contains TDI
12. Mine Shield	Fair	Fair	Poor	2.7×10^{-3}		None	None	None	Brittle
13. Miracote	Excellent	Good	Fair	1.1×10^{-4}		None	None	None	Low elongation
14. Butyl/Nylon Membrane	NA	Excellent	Good	1.6×10^{-5}		NA	NA	Medium	Flammability?
15. EPDM/Nylon Membrane	NA	Excellent	Good	2.5×10^{-6}		NA	NA	Low-Medium	Flammability?

NA = Not Available
* = $Cm^2 S^{-1}$

TABLE 4

APPROXIMATE COSTS FOR EXPERIMENTAL 300cm x 460cm BULKHEADS

Materials		Labor (Man-Hours)
1. Basic Structure		
4 ea. 10cm x 10cm x 300cm at ∿ 1¢/cm	$16	16
5 ea. 5cm x 15cm x 370cm at ∿ 1¢/cm	18	
6 sheets 13mm x 10cm x 20 cm plywood @ $7/sheet	42	
Nails and misc.	4	
	$80	
2. Sealing Bottom of Bulkhead		
3 bags cement	$15	4
3. Application of Urethane Foam Sealant		
1/2 Rigipak Unit @ $260 ea.	$130	1
4. Filling of Rock Cracks Adjacent to Bulkhead		
2 bags gypsum cement	20	4
Disposable airgun cartridges	4	
	$24	
5. Application of Aquafas to Bulkhead (trowel application with seam reinforcement)		
Assume 1.5mm thick, or 45 liters at $2.40/liter	108	4
Scrim and misc.	4	
	$112	
6. Application of Aquafas to Adjacent Wall (90cm wide) 13.5m^2 @ 1.5mm at $2.40/liter	$90	2
7. (Alternative to 5) Application of Rubber Membrane		
EPDM Membrane (1.12mm x 18.6m^2) at $8.61/m^2	160	4
4 sheets 6mm plywood @ $5/sheet	20	
One 15 liter unit Vertical Grade Liquiseal	70	
Nails, disposable brushes and misc.	5	
	$255	

TOTAL COST	Aquafas Bulkhead	Rubber Membrane Bulkhead
Materials	$451	$594
Labor	31 man-hours	31 man-hours

or suspend operations during the period when this program was to be conducted. Site selection was thus both aided (by quickly narrowing possibilities) and hampered by the smaller number of options. We initially wrote to Atlas Minerals, Division of Atlas Corp., since we had recently completed tests on sealants in their Pandora mine at LaSal, Utah, and our familiarity with their staff, operating procedures, and policies made the possibility of such a renewed relationship seem particularly attractive. Unfortunately, intensified pressures to improve the productivity of their uranium mining operations in the Moab, Utah area made it impossible for them to cooperate in this program. Other companies (Sohio, Exxon, and several others) were in process of reducing operations. Favorable responses were given by Union Carbide Corporation and by Rio Algom Corporation, both operating mines in the Paradox and Lisbon Valleys of Colorado and Utah. Arrangements were made to visit the King Solomon mine (Uravan, Colorado) and the LaSal mine (LaSal, Utah), both owned and operated by Union Carbide Corporation, and to the Lisbon Mine (LaSal, Utah), owned and operated by Rio Algom Corporation. At two of these sites, the King Solomon Mine near Uravan, Colorado, and the LaSal mine, in LaSal, Utah, potential underground sites were inspected and a number of measurements of radon concentration and working level were made. At the Lisbon mine, discussions with the mine supervisor and ventilation engineers convinced us that the available sites were not nearly as well suited to our needs as those at the King Solomon and LaSal mines. The King Solomon and LaSal mines were served by inclined roadways, an attribute that had obvious advantages in convenience and savings of time, labor and expense in conducting a test while active mining was in progress. Table 5 lists salient characteristics of each of these mines for comparison.

Both sites had double entries, permitting two bulkheads to be erected and tested simultaneously, with both bulkheads therefore exposed to essentially identical conditions of radon concentrations, atmospheric pressures, volume of confined air and ground characteristics. The LaSal mine site was preferred and recommended because of a number of individually modest advantages it offered, most of which are noted in Table 5. The interstitial radon concentrations were less than the desired minimum of 100,000 pCi/l in both sites, but we believed not so much less as to cause any problem in evaluating the bulkheads.

On the basis of all factors available, the LaSal mine was suggested to, and accepted by, the TPO as the site for this study. A modification of the Scope of Work to permit the use of double-entry stopes was agreed to.

The selected site, located in the LaSal mine, was a double entry stope with a volume of approximately 2000m^3. The two entry-ways were on an airway leading directly to the main exhaust airway. An abandoned lunchroom located some 170 meters away was available as a location for data acquisition systems, the computer, and as storage. Electrical power was readily available to both the lunchroom and to the rib between the two entryways to the stope.

TABLE 5

FACTORS FOR MINE SELECTION: KING SOLOMON VS. LASAL

Factors	King Solomon	LaSal
I. Access		
a. to mine	mountain road, unpaved, could be dangerous in winter	level road, mostly paved, near state highway
b. to test site	"Scout" could be driven to underground site	"Scout" might not be able to negotiate underground passages but tractor available on loan.
c. to input air	easy	some re-direction necessary, vent - tubing and temporary stopping
d. to signal cable	easy	easy
e. to exhaust airshaft	distant	close
f. electric power	easy, but would have to be supplied	already available at unused underground lunch-room
II. Test Site		
a. volume	∿3700 m^3	∿2300 m3
b. present WL in stage:	>80 (unventilated)	>12 (some ventilation)
c. present WL in air of haulage at stope entry:	∿1	∿0.7
d. interstitial radon concentration in long-holes	56 nCi/1 32 nCi/1	44 nCi/1
e. entries	2, spaced 13 m apart on same air-way	2, spaced 23 m apart on same air-way
III. Instrumentation Lab		
a. on surface	none: building would have to be erected	some space available in safety-office trailer
b. underground	none: building would have to be erected	unused lunchroom with electric power available close to test site
IV. Overall Evaluation:	acceptable	acceptable; preferred

D. Arrangements for Mine Use; Subcontract Agreement

Arrangements to use the LaSal mine of Union Carbide Corp. were made with Mr. Niels Haubold, Manager of Mines, Union Carbide Corp. Metals Division, and Mr. Bruce Green, Superintendant of Mines, LaSal Area Mines of Union Carbide Corp. (see Appendices A-3 and A-4). In addition a subcontracting agreement for time and materials was signed with Union Carbide Corp. for their efforts in conjunction with the performance of this program.

V. PHASE TWO - FIELD TEST

A. In-mine Transportation

The diesel-powered vehicle used on a prior underground mine program was available for use on this program. Out intent was to use this vehicle (an International Scout) for both surface and in-mine transportation. However, mine staff recommended that we not attempt driving the 1150-meter inclined haulage until it was enlarged and improved, a project which was then underway. For a period of about 30 days, in-mine transportation was a problem, particularly transport of bulky or heavy items. Again, due to depressed market conditions, the mine was operated with minimal staff; hence on occasion it was necessary that we become proficient in the operation of articulated vehicles, to avoid inordinate delays. Continued improvements on the inclined haulage permitted use of the Scout beginning December 20th.

B. Site Preparation

The site was prepared by constructing bulkheads and brattice curtains to control air direction, installation of a dual 10 hp Spindrift fan to supply relatively clean air to the site, and laying of some 170 meters of 61-centimeters diameter vent bag to complete this secondary ventilation system. The location of this system is shown in Figure 1, the map of the test site. The area enclosed behind the bulkheads is shown in gray. The test bulkheads were located at points B-1 and B-2.

Initially one bulkhead (D) and three brattice curtains (A', C, and E) were constructed at the points shown on the map. An additional bulkhead was later constructed at A" to further improve air quality. Consideration was given to construction of additional bulkheads for further management of air flow and radon concentration control, but since these would likely have led to relatively dead-air areas containing high uncontrolled radon concentrations, those plans were abandoned.

Locations of continuous radon detectors are indicated on the map of the test site. The positions of the air sampling tubes for these detectors were determined by surveying air velocities in the cross-sectional plan at each sampling location and selecting a position representing the average air velocity at that location. Union Carbide electricians supplied the area with 30 amperes of 110 volt power connected to a 20-outlet board located at P, which was sufficient to power all detectors at the site.

The two Data Acquisition System (DAS's), signal receivers, and the Apple II computer were positioned in an unused former lunchroom (now called the instrument laboratory), and signal cable was laid from the laboratory to the 20-outlet electrical supply board and nearby signal transmitters (at P), a distance of approximately 140 meters.

A short (approximately 25 meter) side stub just beyond and to the right of the vent bag exit (B) was ventilated by two 51 cm window fans (shown in Figure 1) to improve the stability of radon concentrations in air that might be drawn into the main ventilation stream. Problems involving signal instability in the data acquisition system were solved by Mr. Wayne Howie of USBM/SRC, who traced the difficulty to the lack of sufficient cable length in the signal transmission lines between multiplexers. Additional lengths were inserted to correct the fault. Necessary detector correction factors were inserted in the system for all but the temperature sensor (for which the correction factor calculation supplied was found to be erroneous. The proper factor was applied to all temperature data at the end of the tests). Mr. Howie also replaced a printer in one of the two DAS's.

Air Control

Bulkheads and air curtains of brattice cloth were constructed or hung at points A', C, D, and E shown in Figure 1. Blasting in an area immediately adjacent to, and below the test site necessitated frequent re-setting/re-building of A' and A'''. To reduce the blasting-induced problem with curtain A', a bulkhead consisting of lagging, chainlink fence, and brattice cloth was constructed at site A'', which also reduced the effect of the waste air infiltrating A (and hence B) from the direction of the instrument laboratory. Air curtains are notoriously leaky due to the inability to effectively seal off the upper rib and back area. Unfortunately, bulkhead A'' suffered from these very defects, and was probably no more than 85 - 90% effective at best. The prime source of contaminated air, however, came from the large bulkhead (erected and maintained by the mine operator) immediately adjacent to A'''. Attempts to reduce air infiltration into A from this source was not very successful, with the result that this air travelled approximately 170 meters through open drift (not including crosscuts and other drifts opening onto A) before joining the air emerging from the vent bag. This air was by far the largest contributor to the total air volume ($\sim$625 m^3/min.) flowing through F and to the background radon concentration at the sampling locations.

Consideration was also given to constructing a more substantial air curtain at E, but was abandoned because it was felt that the pulling force of the upcast fan nearby would necessitate creating an exit port best described as a controlling orifice. The creation of such a controlling orifice at this point had two disadvantages. First, it would have severely restricted traffic-flow between the test site and the instrument room. Second, it would have tended to destabilize air flows in the rather complex system of partially-bulkheaded drifts adjacent to the test site, probably making radon concentrations vary severely at the sampling locations.

Mining was later discontinued in the drift almost immediately below the test area, hence blasting no longer occurred beneath the experimental bulkheads and lessened the need to re-set air curtains as frequently as previously, but continued to control the sources and flows of ventilating air through the passageways leading from haulageway A (see Figure 1) to the bulkhead test site. Because much of the available air was being drawn out of the upcast vent just north of E, it proved to be very difficult to reduce the normal radon concentration in air flowing through below about 0.5 nCi/l. Working Level measurements in drift F typically ranged between 0.5 and 1.0 WL.

C. Experimental

1. Background Data Collection

The initial phase of experimentation, monitoring of the test area background levels prior to installation of the test bulkheads, was done during the period December 5, 1981 to January 6, 1982. During this period, additional efforts to control air quality and quantity through drift F were made. A bulkhead (A") was erected to replace air curtain A' (which was constantly being displaced due to the air shock from nearby blasting). An air curtain was also erected in a drift upstream of the vent fan. Air in this drift was thought to contribute to the poor air quality being taken into drift A. In similar fashion to A', this curtain was constantly subject to air shock waves. Since this drift was in an area currently being mined, a more permanent control device could not be built, and further attempts to control this source of radon-laden air had to be abandoned. Considerable erratic behavior can be seen in the data (Figure 3 and Table 6) but on average the radon concentration increased 138 ± 162 (2σ) pCi/liter between detector 48, positioned in drift F (and upstream of the projected site for bulkhead B-1), and detector 52 also positioned in drift F (and downstream of the projected site for bulkhead B-2) during the background period. Power interruptions were frequent during this time period. Data obtained during known power outages, or periods of poor air direction control have been deleted from the calculations.

Surfaces in the immediate vicinity of bulkhead locations were prepared for eventual sealing by removing loose rock and sand on the floor for a distance of 120 to 160 centimeters towards drift F and washing the ribs and back to remove dust. The floor was backfilled with hand-mixed concrete to an average depth of 5-10 cm. A coherent surface on the ribs and back was created by application of gypsum cement to facilitate spraying with Aquafas 48-00 at a later date.

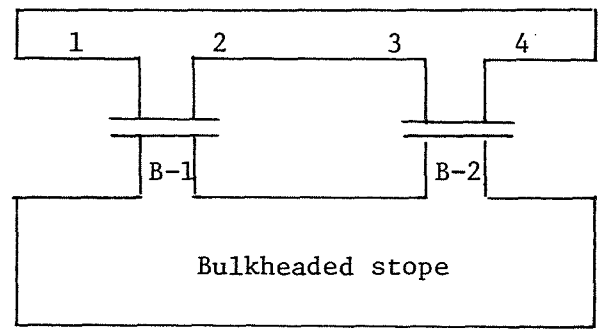
Also during this period collars to contain flux canisters were placed at two elevations at distances 30, 60, and 120 cm from the expected construction plane of the bulkheads, to permit monitoring of the radon flux emanating from the rock. This monitoring was expected to yield information regarding radon activity in the rock in the immediate vicinity of the test bulkheads. Data on radon flux, and use of flux canisters are presented in Section H.

TABLE 6

Increments in radon concentration observed between paired detectors, before and after each bulkhead.

Period *	Radon Concentration increment, pCi/l		
	ΔB-1	ΔB-2	Δdrift
2	14±16	138±162	5±200
3	10±37	45±120	-45±211
4	33±30	12±101	60±183
5	41±19	12±131	63±128
6	46±16	12±84	64±61

Sketch identifying detector locations



ΔB-1 across bulkhead B-1, detector 2 minus detector 1
ΔB-2 across bulkhead B-2, detector 4 minus detector 3 with detector 4 corrected for correctable time lag
Δdrift detector 4 minus detector 1

* Period 2 - Background
3 - Totally sealed (passive restraint)
4 - Natural convection (open bleeder)
5 - Forced convection (pumped bleeder)
6 - Forced convection through charcoal

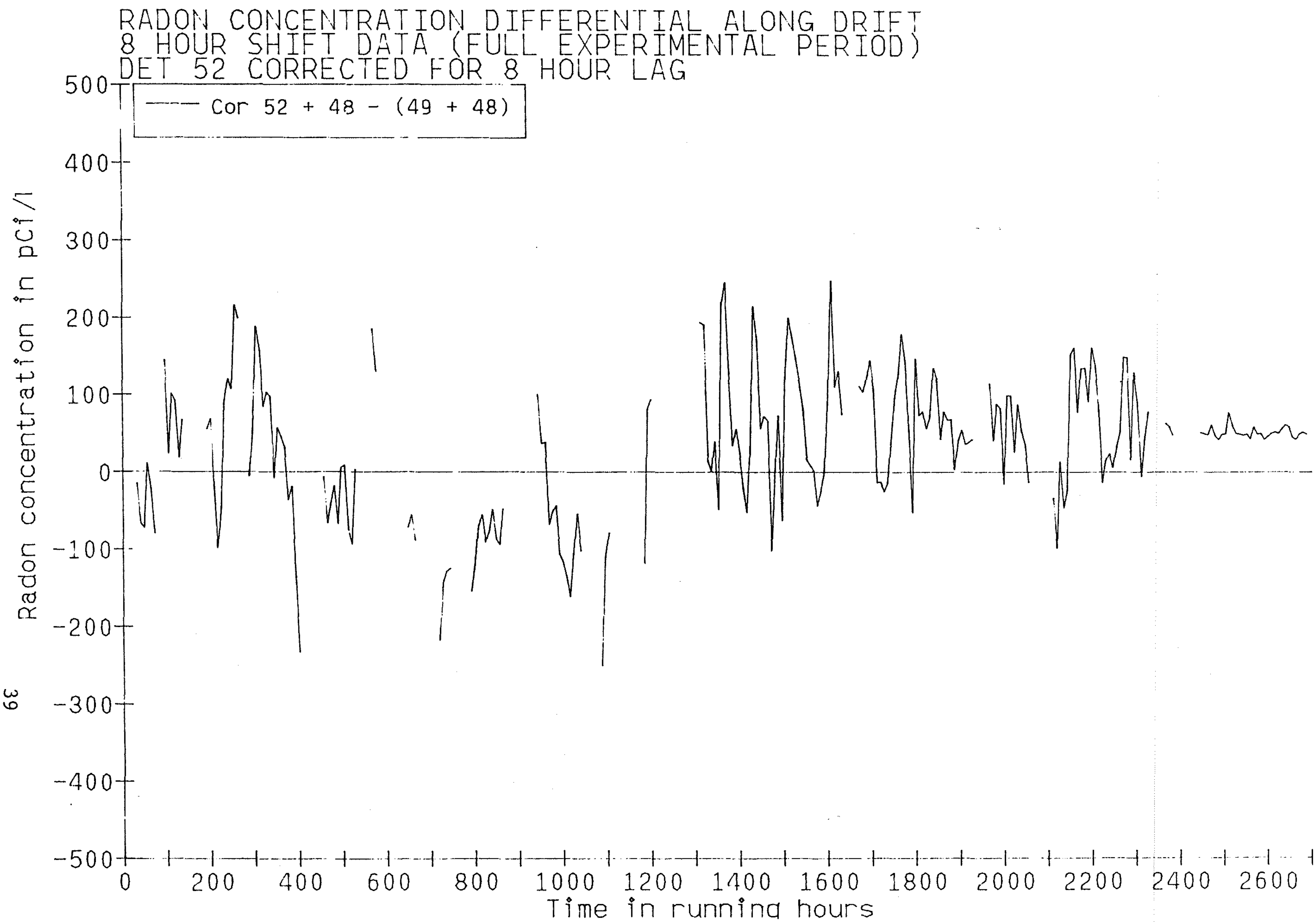


FIGURE 3

RADON CONCENTRATION DIFFERENTIAL ALONG DRIFT
8 HOUR SHIFT DATA (FULL EXPERIMENTAL PERIOD)
DET 52 CORRECTED FOR 8 HOUR LAG

2. Bulkhead Construction

The two bulkheads were constructed during the period December 16 to December 20, 1981, and membrane application begun on December 27th. 15 cm-by-15 cm timbers were used as uprights, and 5 cm-by-15 cm boards were nailed horizontally to the timbers. Patterns of rib, back, and floor contours were made on cardboard, and 13 cm plywood cut to conform to the patterns (see Figures 4 through 11, showing construction). The fitted plywood was nailed into place, and the center sections then removed to allow air flow through the bulkheaded stope until the bulkheads were to be sealed. Holes were drilled at desired locations for positioning of bleeder-pipe and sampling lines.

Bulkhead B-1 was sealed by applying the EPDM membrane as a single sheet over the 13 cm plywood, and covering the membrane with 6 cm plywood. Liquid rubber sealants designed for use in vertical and horizontal applications were used to seal the edges of the EPDM sheet to the back, ribs, and floor of the drift. The small gap between the fitted plywood and the rock itself was filled by application of a foam-in-place polyurethane available from Mine Safety Appliances. Bulkhead B-1 is therefore a laminate of plywood-membrane-plywood on a timbered support frame.

Bulkhead B-2 also had a small gap between the fitted plywood and the rock itself, which was filled with foam-in-place polyurethane, and the entire surface then coated with Aquafas 48-00. The rough, thick coating was evened using a serrated trowel having 4 mm teeth, and smoothed using a paint brush, creating a relatively uniform coating approximately 4 mm thick. Final sealing of B-2 was delayed several days while the drums containing the charcoal (positioned behind B-2) were repeatedly sealed and tested for leakage.

3. "Passive Restraint" Period

The "passive restraint" period extended from January 6, 1982 to January 29, 1982. Continuous radon monitoring indicated an average radon concentration increase of 10 ± 37 (2σ) pCi/liter from a point upstream of bulkhead B-1 to a point downstream (detector 46 data minus detector 48 data), and an average radon concentration increase of 45 ± 120 (2σ) pCi/liter from upstream to downstream of bulkhead B-2 (detector 52 data, time-compensated, minus detector 51 data). We had expected to observe an increase in radon flux through the rock in the immediate vicinity of each bulkhead, and were prepared to seal an area extending one meter out from each. The data did not support this expectation (see Table 7), but as a precaution these areas were sealed by application of Aquafas 48-00, the material applied to bulkhead B-2. The metal collars were removed from the rock, then reset after sealant application. Beginning on February 3rd, radon flux was observed to quickly decrease from normal levels (see Table 7) to a level indistinguishable from that of blanks, and to remain at that level for the remainder of the experiment.

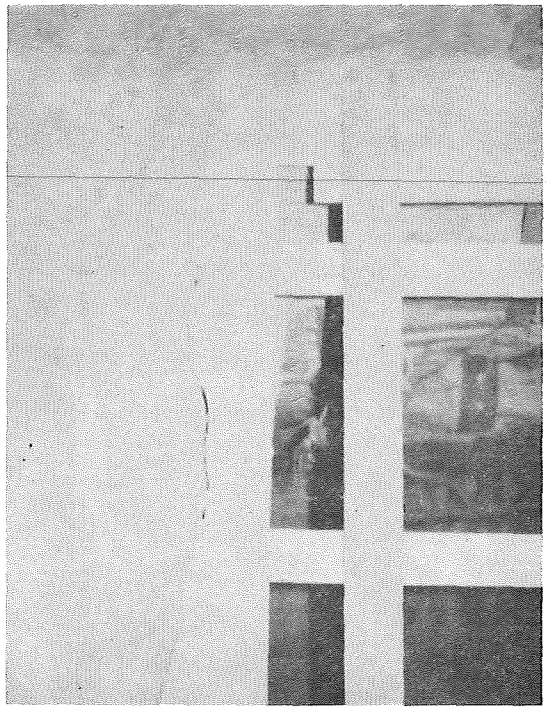


FIGURE 4 - B-1 Under Construction

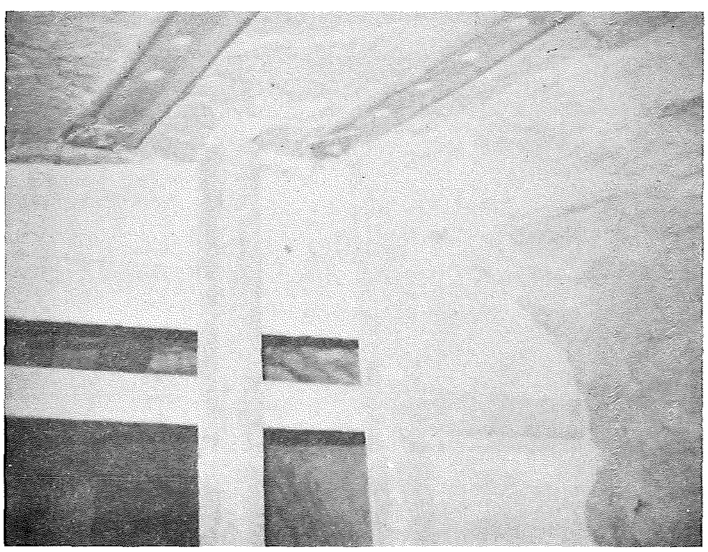


FIGURE 5 - B-1 Under Construction

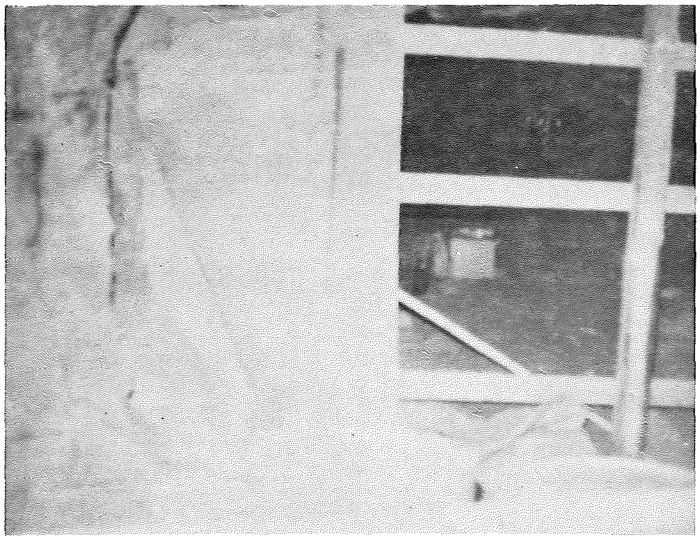


FIGURE 6 - Bulkhead B-2 Construction

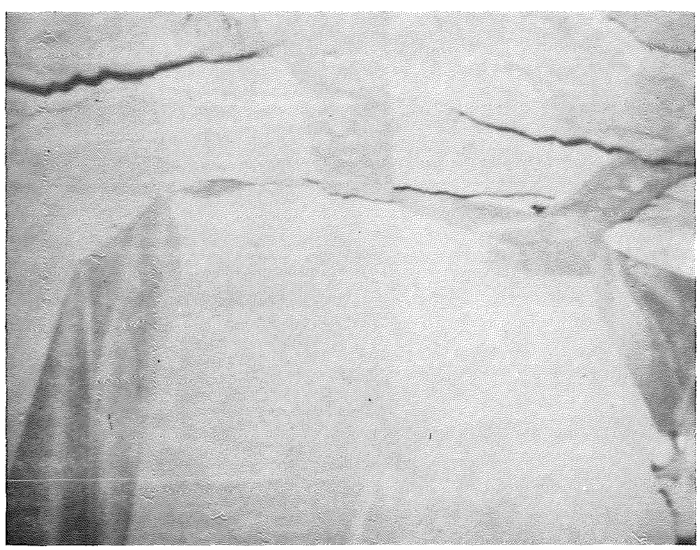


FIGURE 7 - Membrane Application Bulkhead B-1

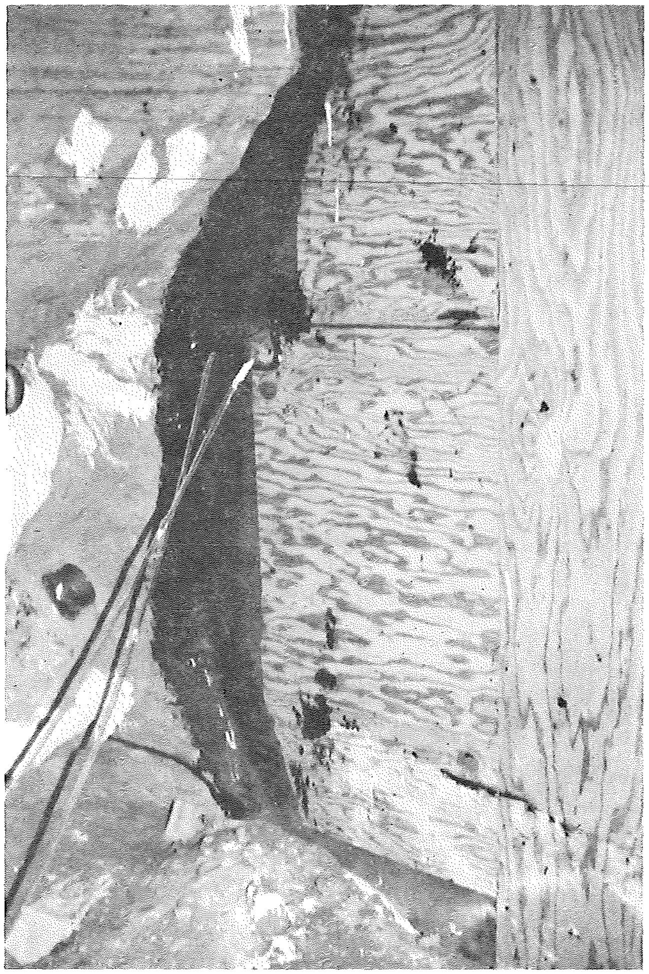


FIGURE 8 - Bulkhead B-1 Contruction,
Left-side Detail

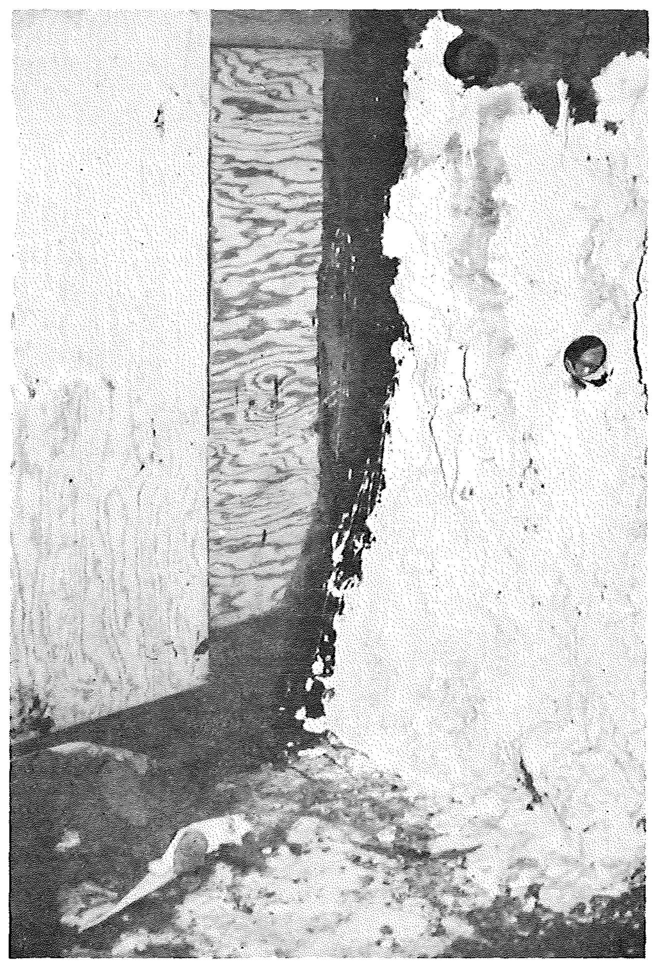


FIGURE 9- Bulkhead B-1 Construction
Right-side Detail

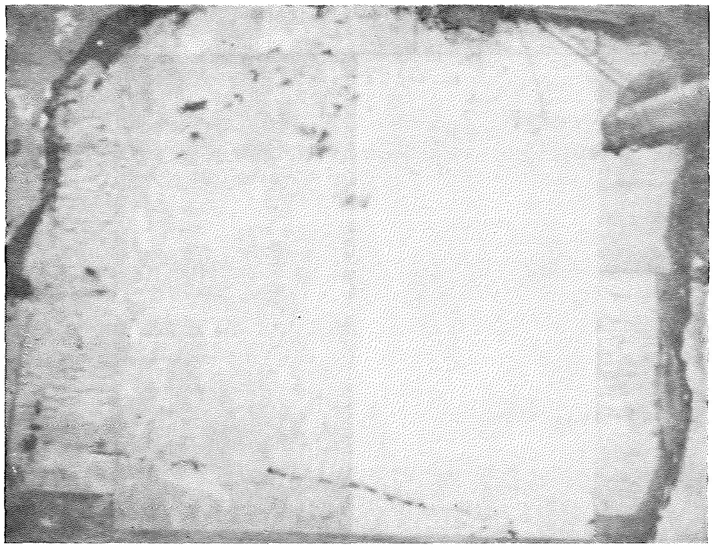


FIGURE 10 Bulkhead B-1

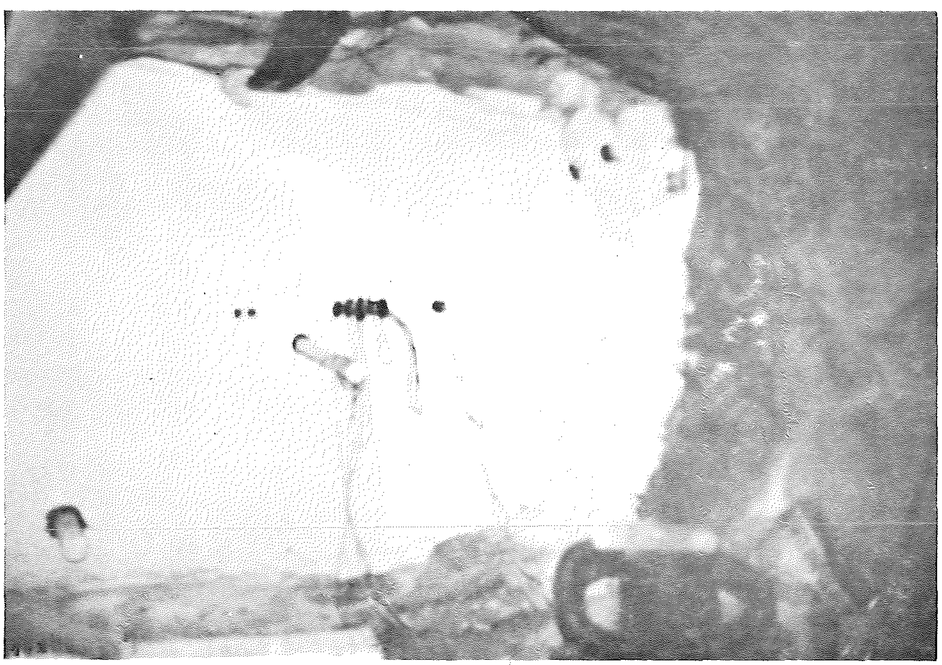


FIGURE 11 Bulkhead B-2

TABLE 7

Flux Data, Sites on Ribs Adjacent to Bulkheads, in Units of Ci cm^{-2} sec^{-1} x 10^{-14}

Date	1LL1	1LL2	1LU1	1LU2	1LU4	1RL1	1RL2	1RL4	1RU1	2LL1	2LU1	2LU2	2RU1	2RU2	2RU4	Barometric Pressure*	Conc in pCi/l Behind bulkheads	
																	B1	B2
12/22	NA	NA	7.39	NA	NA	15.5	NA	NA	9.48	3.30	3.88	NA	NA	NA	NA	NA		
12/23	NA	NA	13.8	3.03	1.70	19.5	NA	NA	NA	NA	2.94	NA	2.13	1.16	2.25	609(o)		
12/23	NA	NA	20.8	6.29	2.64	14.9	NA	NA	NA	NA	2.73	NA	7.28	2.22	1.99	609(o)		
12/27	8.84	7.91	2.81	8.58	NA	21.2	11.3	8.63	10.7	NA	NA	NA	NA	NA	NA	603(+)		
12/28	NA	NA	NA	NA	NA	NA	NA	NA	NA	2.72	3.27	2.56	2.72	4.21	2.78	609(o)		
12/28	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.91	4.43	2.60	2.21	3.03	3.72	608(o)		
12/29	3.90	14.3	2.95	26.8	NA	NA	6.91	NA	14.3	NA	NA	NA	NA	NA	NA	610(+)		
12/29	6.32	13.8	4.08	9.78	NA	NA	25.2	NA	13.8	NA	NA	NA	NA	NA	NA	610(+)		
1/04	6.56	8.64	NA	7.88	NA	NA	21.6	NA	15.2	NA	NA	NA	4.68	3.73	NA	NA		
1/05	14.1	NA	NA	NA	NA	NA	NA	NA	22.3	10.5	NA	13.4	7.41	10.4	NA	NA		
1/06	2.95	8.24	NA	8.31	NA	NA	22.5	NA	13.7	5.64	3.86	NA	3.4	NA	NA	NA		
1/08	3.58	5.50	NA	2.49	NA	NA	6.15	NA	11.7	1.63	4.38	NA	2.83	NA	NA	620(-)	10,100,	11,500
1/11	18.6	24.4	NA	NA	NA	NA	NA	NA	24.1	77.8	25.8	16.3	12.2	27.0	NA	608(o)	27,200,	26,900
1/12	7.20	12.0	NA	11.4	NA	NA	24.2	NA	13.1	26.1	7.52	7.65	5.62	5.18	NA	604(+)	30,800,	33,500
1/13	1.89	3.89	NA	0.27	NA	NA	4.34	NA	3.48	1.40	1.94	1.86	0.89	1.70	NA	610(+)	27,000,	31,900
1/14	7.26	10.8	NA	7.25	NA	NA	10.7	NA	9.12	9.28	5.36	4.14	3.50	3.40	NA	610(o)	26,600,	26,300
1/15	4.01	8.23	NA	6.61	NA	NA	11.3	NA	9.13	8.81	3.77	2.38	2,19	2.38	NA	608(o)	29,800,	32,800
1/18	7.53	12.0	NA	11.1	NA	NA	25.3	NA	13.7	22.1	6.62	5.96	4.58	6.23	NA	605(o)	24,500,	36,900
1/19	12.1	10.8	NA	15.7	NA	NA	24.9	NA	17.4	43.4	6.42	5.73	4.69	5.28	NA	604(o)	34,400,	37,200
1/20	4.04	8.40	NA	8.25	NA	NA	19.3	NA	13.2	14.3	5.87	5.97	4.41	3.53	NA	605(o)	33,800,	37,300
2/3	1.19	1.04	NA	NA	NA	NA	0.88	NA	0.99	0.80	1.41	1.08	NA	2.00	NA	604(o)		
2/5	0.53	0.39	NA	NA	NA	NA	0.56	NA	0.17	0.29	0.94	0.87	NA	0.76	NA	612(+)		
2/9	0.57	1.49	NA	NA	NA	NA	0.27	NA	0.19	0.69	0.39	0.60	NA	0.39	NA	610(o)		
2/12	0.37	0.03	NA	NA	NA	NA	0.38	NA	0.22	0.54	0.45	0.53	0.24	0.22	NA	620(o)		
2/22	0.33	0.68	NA	NA	NA	NA	0.66	NA	0.59	0.66	0.79	0.68	1.43	0.74	NA	614(o)		
3/12	1.13	0.95	NA	NA	NA	NA	0.77	NA	0.40	0.61	1.29	0.49	1.48	0.61	NA	610(+)		
3/18	0.48	NA	NA	NA	NA	NA	0.83	NA	0.52	0.92	0.78	NA	0.91	0.92	NA	610(o)		
3/25	0.38	0.36	NA	NA	NA	NA	0.49	NA	0.27	0.47	0.35	0.63	0.50	0.47	NA	613(o)		

Barometric pressure change during the three hours preceding sampling: *(o) = Steady, (+) = Rising
(-) = Falling

In addition, three collars were affixed to each of the two bulkhead surfaces, and radon flux determined at these sites. These data, also, were not distinguishable from those obtained from blanks.

Concern over the apparent inability of two continuous radon detectors monitoring the same ambient air to agree, (in one case air intakes were side by side, and in another two detectors were sampling in series) led to a series of investigations into detector behavior. The high voltage applied to the detector photomultiplier tube was observed using a digital voltmeter and, where necessary, adjusted to the indicated correct voltage. Each detector was also tested by replacement of the scintillator flask with a piece of zinc sulfide paper and a thorium-230 source. Neither procedure resolved the problem of two detectors not reading similarly. Four detectors were now connected in series, all sampling the same air by connecting the intake of the second to the outlet of the first, etc. Similarly two other radon detectors were connected in series (see data, Table 8). Ultimately, two of the first four detectors were removed from service, and only data from the first three detectors in the drift, detectors 48, 46, and 51 were used from that time on. Data from detector 52, (located at brattice E), however, continued to lag the other detectors by approximately eight hours (see Figures 12 and 13), and was time-compensated in all data calculations. Detector 44, being held for use during the radon-adsorption-on-charcoal phase was operating at the junction of airway F and the drift leading to bulkhead B-2 (see mine map, Figure 1), and seemed to agree reasonably well with detector 51 sampling airway F approximately twenty feet upstream. However, differences in readings among detectors were never totally resolved. A portion of the problem was later traced to a partial loss of input power when more than one detector was connected to the same 30 meter extension cord. An additional portion of the problem could have been a partially-pinched air-line leading to the detector flasks.

4. Natural Convection, Or "Open Bleeder" Period

On January 29th, a 100 mm vent in bulkhead B-2 was opened, and connected to flexible 100 mm dryer vent hose leading into an exhaust airway. The radon concentration behind the bulkhead at this time was approximately 35,000 pCi/1. This non-forced-convection period, also called the "open bleeder" period was continued through February 18, 1982.

During this time period the average radon concentration difference upstream and downstream of bulkhead B-1 (detector 46 data minus detector 48 data) was determined to be 33 ± 30 (2σ) pCi/1, and the average radon concentration difference upstream and downstream of bulkhead B-2 (compensated detector 52 data minus detector 51 data) was 12 ± 101 (2σ) pCi/1.

5. Forced Convection Period

A novel portion of our experimental plan involved the use of a differential pressure transducer to monitor, and signal, the pressure

TABLE 8

Observed radon concentrations when detectors were sampling in series.
Order of series: 49 → 48 → 46 → 47, 51 → 52
Time: 1100 019 to 0800 020

Time	Detector:	49	48	46	47	51	52
1100		536	363	523	388	449	510
1200		573	411	592	437	436	512
1300		707	469	673	576	443	494
1400		844	540	757	617	448	504
1500		896	543	800	649	453	488
1600		826	501	728	596	468	511
1700		770	448	675	555	452	532
1800		745	443	642	549	459	522
1900		690	414	611	518	462	522
2000		627	393	547	467	473	531
2100		557	343	499	436	477	539
2200		535	327	474	390	459	545
2300		496	301	446	376	475	537
0000		478	292	447	377	460	522
0100		500	295	445	385	460	530
0200		572	343	493	422	439	519
0300		612	373	534	445	453	505
0400		634	374	555	472	445	515
0500		662	389	562	484	445	493
0600		649	384	552	473	437	482
0700		657	385	567	480	451	475
0800		641	392	559	456	539	473

Data during time 49, 48, 46, 47 were linked in series, and 51 and 52 were also linked together in series.

TABLE 9

Typical data before removal from service of Detector 49 (paired with Detector 48) and Detector 47 (paired with Detector 46).

Time	Detector:	48	49	46	47	51	52*
			1700 022 through 0700 023				
1700		323	361	382	533	417	432
1800		306	352	383	522	410	444
1900		316	355	370	525	413	430
2000		292	329	352	526	407	416
2100		276	332	353	505	395	417
2200		286	330	349	485	376	418
2300		272	318	354	468	348	421
0000		263	315	347	460	362	
0100		260	309	343	459	363	
0200		260	311	331	436	363	
0300		269	295	337	445	364	
0400		283	333	355	473	403	
0500		317	367	393	490	408	
0600		320	373	405	504	432	
0700		326	393	423	519	454	

*corrected for response time delay

TABLE 10

Typical data after removal from service of Detectors 49 (previously paired with Detector 48) and Detector 47 (previously paired with Detector 46).

Time	Detector:	0000 through 1200 026			
		48	46	51	52*
0000		425	432	460	615
0100		444	456	494	620
0200		528	564	560	642
0300		552	588	588	641
0400		587	616	631	633
0500		611	631	648	582
0600		617	663	686	0
0700		622	646	683	0
0800		631	655	686	0
0900		593	634	667	0
1000		540	557	598	631
1100		516	551	568	635
1200		516	563	579	654

*corrected for response time delay

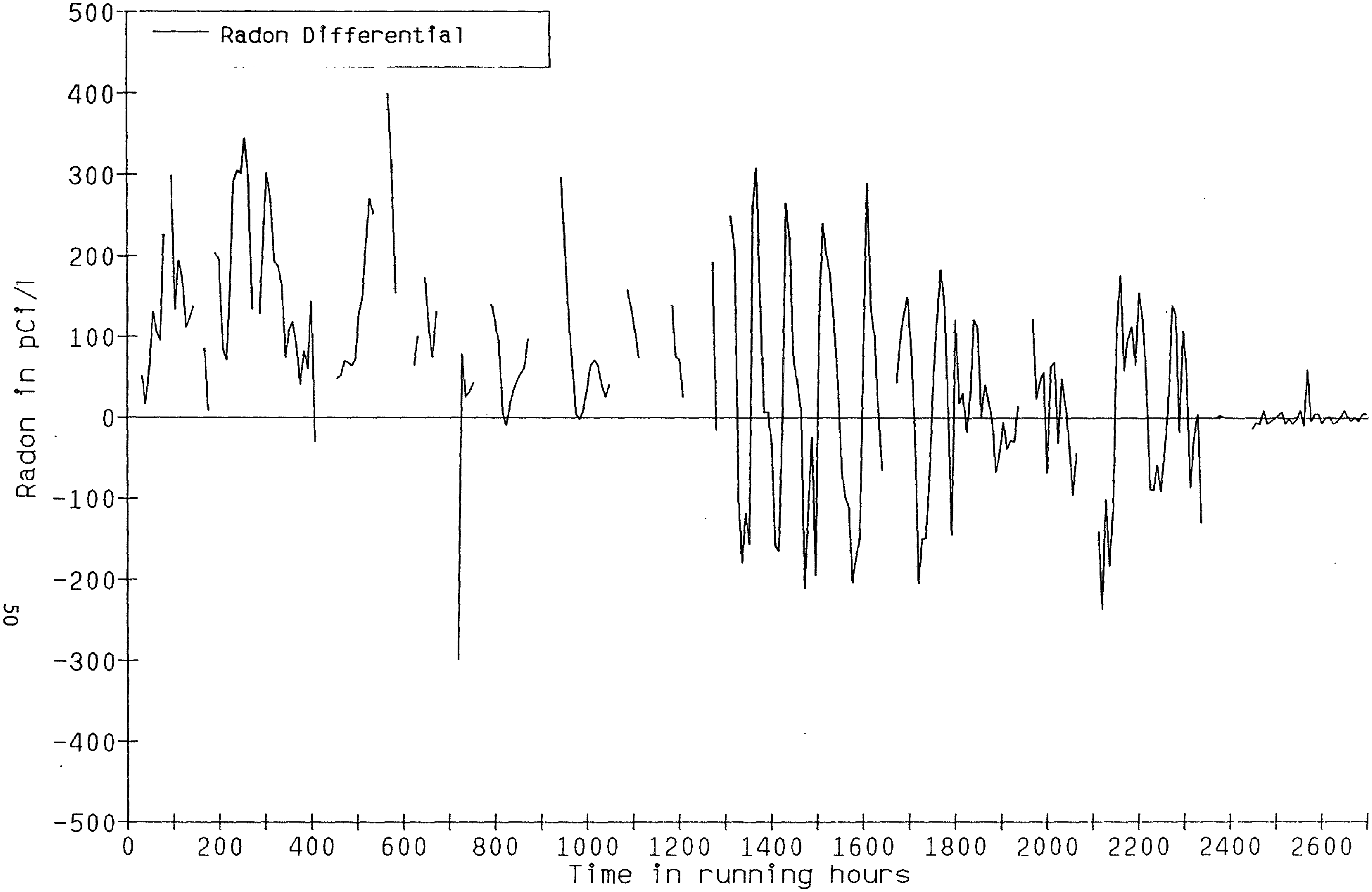


FIGURE 12

RADON DIFFERENTIAL

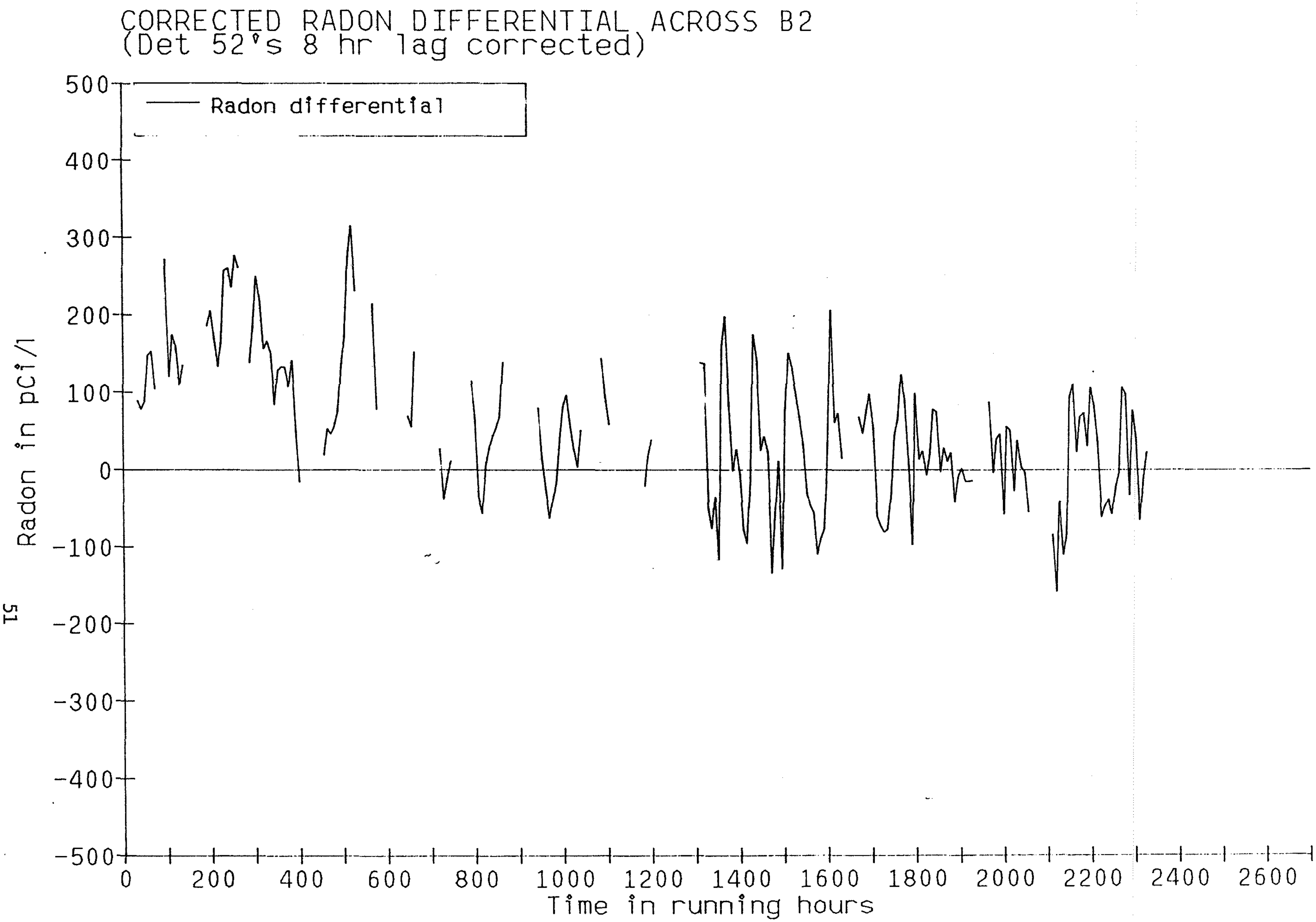


FIGURE 13

CORRECTED RADON DIFFERENTIAL ACROSS B2
(Det 52's 8 hr lag corrected)

differential across one of the experimental bulkheads. This signal could then serve to control electrical power to a forced-convection fan, and be adjusted so as to turn the fan on only when the differential decreased to less than a pre-determined value. Two such transducers (an intentional redundancy) were installed in bulkhead B-2, and a servo-control box was constructed for our use by Mr. Wayne Howie of USBM/SRC. The "fan-powered forced exhaust" period was begun on February 19, 1982, using the same dryer vent tubing formerly used during the "natural convection" period, and simply attaching a 0.5 hp (servo-controlled) centrifugal fan to the outlet end of the vent hose. The adjustable potentiometer on the controller was adjusted to turn the fan on when the pressure differential across the bulkhead was less than 0.5 mm Hg (indicated by a numerical reading of 490), and to turn the fan off when the pressure differential was greater than 1.0 mm Hg (indicated by a numerical reading of 480). The fan was operated for approximately twenty-five seconds out of every one hundred eighty to two hundred seconds, or roughly fourteen percent of the time. During "off" periods the fan exhaust port was not closed or damped. During this experimental test period the radon concentration (on average) upstream and downstream of bulkhead B-1 was 41 ± 19 (2σ) pCi/liter, and upstream and downstream of bulkhead B-2 was 12 ± 131 (2σ) pCi/liter. This portion of the program was terminated on March 4, 1982.

6. Radon Removal in Air Exhausted from Bulkheaded Stope

An additional integral part of the experimental program was the measurement of the effectiveness of activated charcoal for the removal of radon from the small amount of air exhausted from the bulkheaded area in the course of maintaining the necessary pressure balance. A charcoal trapping system to adsorb the radon in the air being exhausted from the bulkheaded area was constructed. The system was located so as to minimize the safety hazard which would exist when the radon adsorbed on the charcoal decayed to its gamma-emitting daughter products ^{214}Bi and ^{214}Pb. The design allowed for essentially complete decay of radon on the charcoal assuming an intermittent flow rate of 100 to 200 ft ^{3}/min (2.8 to 5.6 m^3/min) again taking advantage of periods of favorable pressure differentials. The effects of mine temperature and humidity on the capacity of the charcoal were considered to be relatively minor. The Arthur D. Little, Inc. report to the USBM on "Advanced Techniques for Radon Gas Removal," Contract Report H0230022, dated May 1975 was used as a basis for design and performance considerations and expectations. The pressure drop through the charcoal trap system was the factor ultimately controlling the exhaust air flow rate, which could not be pre-determined.

Six drums of charcoal were sealed by coating with Aquafas 48-00, and placed in position behind B-2. Initial plans were to pull air from behind the bulkhead through the six drums (each containing 91 kg of charcoal) in series, using 50 cm PVC pipe as the conduit. A large Sears shop vacuum was to be used to pull the air through the drums and conduit. Taps in the connecting piping between drums were connected to a radon detector located outside the bulkhead so that the time of breakthrough for each drum could be determined.

Problems associated with leakage of the fiberboard drums (primarily at the metal closure point), and an unexpectedly large pressure drop necessitated a modification of the six-drums-in-series approach. The drums were repositioned as two sets-of-two-in-parallel (see Figure 14). Air was drawn into drums 3 and 4 (see drawing) through pieces of 50 cm PVC pipe extending approximately 76 cm into each of the 91 cm deep drums, and were drawn out through PVC pipe extending approximately 5 cm beneath the surface of the charcoal. The air was pulled in similar manner through drums #1 and #2, through a tee, and out into vent tubing located outside the bulkhead.

Taps were drilled in the connecting tubing between drums #4 and #2, drums #3 and #1, drum #2 and the tee, and drum #1 and the tee (sites marked "x" in the drawing) for monitoring radon breakthrough. Air leaks in the drums were located with smoke (generated from smoke tubes) and eliminated by multiple applications of a rubbery compound called Lap Sealant (purchased for use on bulkhead B-1), available from Carlisle Rubber Company.

The outlet pipes in drums #1 and #2 leading to the tee were covered with aluminum mesh overlayed with cheesecloth to eliminate charcoal fines being pulled into the exhaust system. A change was made from the vacuum cleaner pump to a 0.5 hp centrifugal blower made available by the TPO. This pump, also used on the pump-assisted exhaust phase of the program, was intially thought to be powerful enough to require additional feed air so as not to exhaust inordinately large amounts of air through the bulkhead, thereby greatly reducing useful lifetime of the charcoal. The remedy applied (later found not to be needed) was to incorporate a variable flow damper immediately upstream of the pump. The experiment was terminated on March 26th at 0800 with radon concentrations observed of:

34249 pCi/l	behind bulkhead B-2 ("challenge" concentration)
1306 pCi/l	at the outlet of drum #4
66 pCi/l	at the outlet of drum #2

These measurements indicate that approximately 4% of the "challenge" concentration of radon was not being absorbed by the charcoal in drum #4, and 5% of the radon emerging from drum #4 was not being absorbed by the charcoal in drum #2. No indication was seen of pending breakthrough of radon. (Breakthrough was expected to be indicated by a fairly rapid and progressive rise in output radon concentration.) Since output radon concentration was small and apparently constant with time, the more likely cause of the small leakage rate was either channeling or air leaks or both.

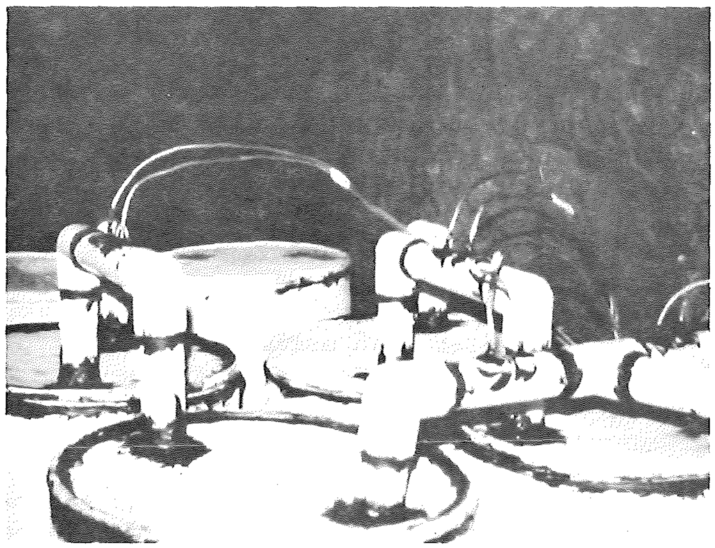


FIGURE 14 Charcoal Drum Arrangement

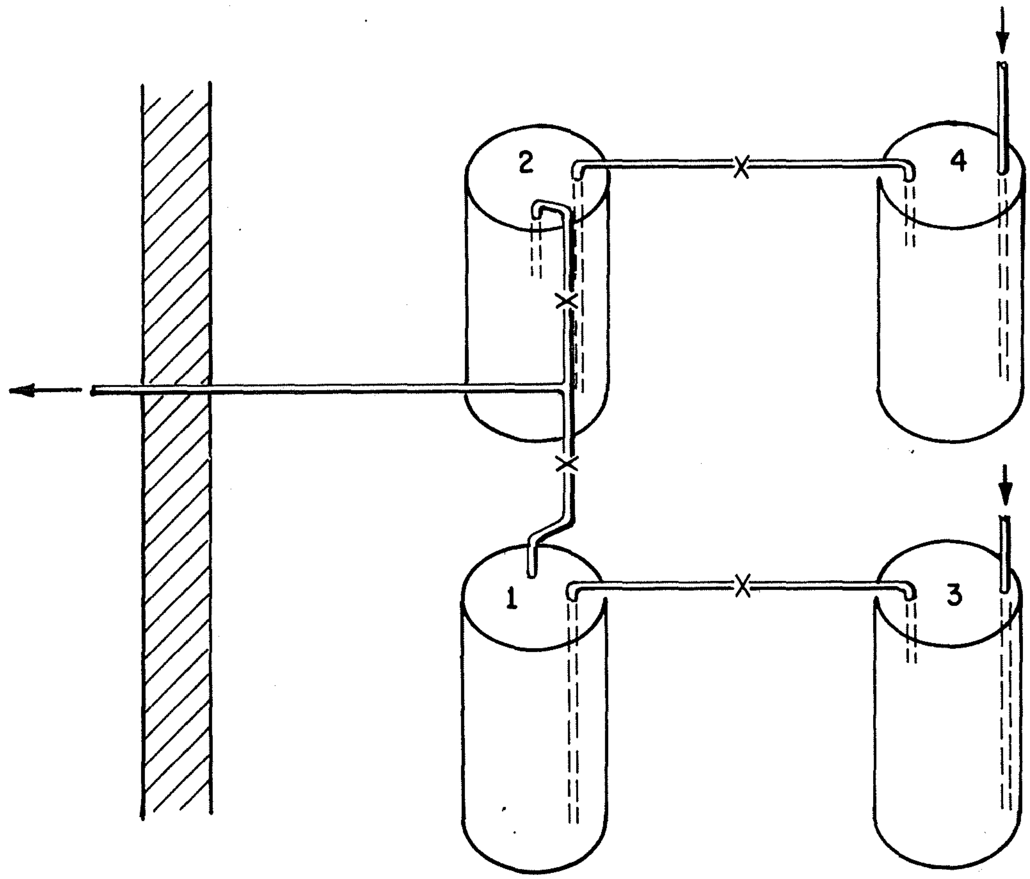


FIGURE 14a
CHARCOAL DRUM SYSTEM

D. Automatic Measurements

1. Instrumentation

The automatic measurement system for atmospheric parameters, of which the USBM Data Acquisition System (DAS) is the central integrating component, was fundamental to the development and recording of the essential data for this program. Two DAS units were provided for our use, giving a total capacity of twenty data channels, ten to each unit.

As in an earlier field test of radon-resistant wall sealant which we conducted on behalf of USBM in 1981 (1), an Apple II microcomputer was connected to the DAS's in parallel with the punched paper tape.

All results of the automatic data acquisition program were recorded by the DAS's and the Apple II microcomputer. Except for periods of general power failure, during which no signals were received, and times when individual detectors were disconnected, malfunctioning or inoperative, all systems recorded data continuously, with readout four times an hour. All of the raw data were recorded simultaneously on punched paper tape and on printed paper tape by the DAS's. The data were converted into true and meaningful engineering units (e.g., pCi Rn/l) and recorded simultaneously on magnetic diskettes and printed on paper by the microcomputer. The computer also calculated and recorded hourly and eight-hourly (shift) means and supplied many other pieces of valuable information for further reference. All of these data were supplied to the TPO at USBM/SRC during the course of the program. In completion of the requirements for this program, the raw data were converted from diskettes to nine-track magnetic tape which are compatible with USBM/SRC's current computation capability, and the tapes and diskettes along with tables to enable programmers to correlate diskette data with data blocks on the magnetic tapes, were sent to USBM/SRC.

All continuous air monitors were supplied by USBM/SRC. The air velocity indicator was made by J-Tec Associates, Inc., Cedar Rapids, IA, and the temperature, and barometric pressure sensors were made by Weather-Measure Corp., P. O. Box 41257, Sacramento, CA 95841. The differential pressure transducers were manufactured by Setra Systems, Inc., Natick, MA and were wired for servo-control of the forced-convection fan by Mr. Wayne Howie of USBM/SRC. The continuous radon detectors were calibrated with either modified (flow-through) Lucas flasks or Eberline flasks, depending on intended usage. Detectors with Lucas flasks were used to sample ambient radon concentration levels while those with Eberline flasks were used to sample high radon levels such as were found in the interstitial sites and behind the constructed bulkheads.

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(1) Lindsay, D. B., J. E. Oberholtzer, and C. H. Summers. Sealant Tests to Control Radon Emanation in a Uranium Mine. Arthur D. Little, Inc. report to USBM/SRC under Contract J0199041. Dec. 1981, 89 pp.

The Working Level detector and atmospheric pressure, relative humidity, air velocity, and temperature sensors were also adjusted and calibrated at USBM/SRC before being sent to the mine at LaSal. Radon backgrounds were again monitored at the mine before placing the equipment underground. One of the detectors, number 51, was observed to have a background level significantly higher than previously observed. A second detector, number 44, was also observed to have a background level considerably different, and nearly significant at the 2σ level.

On completion of underground use, the detectors were returned to the surface where backgrounds were again counted. The pre- and post-experimental background values are listed in Tables 11 and 12. Changes in the background of detectors 40, 41, 42, and 43 were expected since these four detectors were sampling relatively high radon concentration (>20,000 pCi/liter, on average). Detectors 42 and 43 were additionally exposed to high humidity. Water was removed from the sampling lines to these detectors several times during the experiments. Because no basis could be found for choosing a time at which to change the background values and correction factors from pre-test levels to those found after conclusion of the test, it was agreed that the pre-test values would be used for all calculations. Table 13 indicates detector locations and channel assignments.

E. Data Processing

Signals from the various continuous monitors were transmitted to one of two USBM Data Acquisition System (DAS) located in the instrument laboratory, approximately 150 meters from the test area. In addition to the normal outputs of line printer and punched paper tape, data were transmitted to an Apple II computer. The computer and the two DAS's were interfaced exactly as had been done in a previous study (1) which we performed on behalf of USBM in Atlas Minerals' Pandora mine. Thus in addition to raw data, values for each monitor were calculated using background readings and other correction factors, and hourly and eight-hourly means as well as maxima and minima were automatically printed out on standard 216-by-273 mm fan-fold paper.

The availability of calculated data in their proper units, plus the programmed (error detection and indication) printout has decided benefits: malfunctioning monitors are readily detected, allowing prompt remedial action and fewer lost data, and the TPO by having access to copies of recent data can more knowledgeably participate in decision-making.

F. Manual Sampling

Although most of the experimental data were recorded with the

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(1) Lindsay, D.B., J.E. Oberholtzer, and C.H. Summers. Sealant Tests to Control Radon Emanation in a Uranium Mine. Arthur D. Little, Inc. report to U.S. Bureau of Mines, Contract J0199041. Dec. 1981, 89 pp.

TABLE 11

DETECTOR BACKGROUNDS AND CORRECTION FACTORS, CALCULATED AT USBM/SRC BEFORE SHIPMENT TO LASAL

Detector	5 min Background	Correction Factor*
40	45	0.5108
41	37	0.8499
42	47	0.7501
43	79	0.4949
44	81	0.4705
46	146	0.6680
47	218	0.7280
48	42	0.7216
49	43	0.6034
51	102	0.6772
52	67	0.5820
54	56	0.6702
205	2910	5.54E-05

*Correction factors assuming a 5 minute count period.

TABLE 12

POST-EXPERIMENTAL BACKGROUNDS ON DETECTORS - FIVE MINUTE COUNT

Detector	40	41	42	43	44	46	47	48	49	51	52	54
	45	24	121	131	32	156	242	44	51	148	93	68
	38	38	122	135	27	138	223	39	53	143	101	79
	50	27	115	138	27	149	240	36	39	137	80	88
	61	22	113	137	25	187	236	56	68	144	74	70
	48	27	130	168	24	143	238	42	62	186	72	61
	54	34	114	141	18	143	216	50	47	146	87	68
	48	37	120	146	38	156	229	43	59	151	94	87
	40	41	111	152	32	150	266	64	46	150	88	58
	50	24	105	149	29	173	224	51	53	169	69	60
	57	21	107	142	25	134	257	46	45	151	86	62
	53	27	116	130	34	149	231	46	58	148	83	70
	30	26	109	146	32	145	262	53	46	155	95	89
	61	31	119	135	26	140	212	45	47	169	82	57
	46	32	111	134	27	149	237	58	50	140	97	72
	59	34	103	157	27	156	238	50	54	146	94	61
	38	37	95	132	23	149	245	55	50	171	99	73
	42	42	110	116	31	178	260	54	52	150	96	67
	51	32	115	137	29	179	227	48	52	149	76	79
	38	32	118	129	32	163	244	50	49	137	69	76
	41	31	98	143	28	145	205	45	53	130	99	76
	47	27	121	160	26	147	266	70	44	147	82	69
	44	31	124	145	34	150	226	43	48	151	85	70
	53	21	112	127	32	167	225	49	59	143	73	86
	40	34	109	143	27	151	208	53	41	139	85	71
	42	32	113	149	33	151	253	56	47	148	76	67
$\bar{x}$	47	31	113	141	29	154	236	50	51	150	85	72

TABLE 13

DETECTOR LOCATIONS AND CHANNEL ASSIGNMENTS AS OF DECEMBER 3, 1981

DAS No. and Channel No.	Detector	Sample Location	Julian Date/Change, New Location
1-0	40	Behind B-1	
1-1	41	Behind B-2	
1-2	42	150 cm interstitial	
1-3	43	450 cm interstitial	
1-4	44	Between charcoal drums	
1-5	100 Hz Signal		
1-6	pressure	After D, before B-2	349, to 1 - 7 after B-2, before E
1-7	velocity	After D, before B-2	349, to 1 - 6 after B-2, before E
1-8	temp	After D, before B-2	
1-9	WL	Lunchroom	
2-0	48	$\sim$2 meters upstream of vent bag	015, before B-1
2-1	49	Before B-1	025, removed from service
2-2	46	After B-1, before D	
2-3	47	After B-1, before D	
2-4	51	After D, before B-2	025, removed from service
2-5	100 Hz Signal		
2-6	diff. press.	In B-2	
2-7	diff. press.	In B-2	
2-8	R.H.	After D, before B-2	349, removed from service
2-9	52	After B-2, before E	

1) On day 355, attempted replacement of Detector 52 with Detector 45. Detector 45 appeared to be multiple counting, and returned to Detector 52 at 1650 hrs, day 355.

2) On day 015 at 1000 moved Detector 48 back beside Detector 49, sampling output of Detector 49.

3) On day 019, hour 1200 connected outpit of Detector 48 to input of Detector 46. Now have four Detectors in series, all sampling same air.

$$49 \rightarrow 48 \rightarrow 46 \rightarrow 47$$

also connected output of Detector 57 to input of Detector 52 automatic equipment, some measurements had to be made by hand to check the performance of the automatic equipment, and to gather data which could not be obtained automatically.

A vane anemometer was used to aid in siting sampling locations by averaging readings taken over a plane area and sampling at the average location. The vane was also used to determine air velocities at locations and under conditions where the J-Tec could not readily be used.

Air direction and estimates of rate were determined with smoke generated by chemical hydrolysis. MSA smoke tubes were used in all cases. Mapping of areas near proposed bulkhead construction and testing of air restraints was done using smoke tubes.

Working Level determinations as sites not routinely monitored were accomplished using hand-held pumps with filter holders containing glass fiber filters to obtain samples. The samples were then assayed for radon activity using a scintillator, photomultiplier, and counter.

G. EDA Flask Sampling

The apparent inability of detector 52 (located at brattice curtain E) to track changes in ambient radon concentrations as quickly as the other detectors (later determined to be due to a kinked intake line) led us to attempt additional sampling near detector 52 using EDA flasks. Samples taken February 24th indicated radon concentrations approximately 200 pCi/l lower by EDA flask sampling than by the continuous radon detector (see Table 14). Initial suspicions were that flasks were not being evacuated as completely as possible, however, use of vacuum gauges indicated normal (approximately 23.5 inches of mercury) vacuum. Several additional sets of samples were taken with EDA flasks, and all calculated concentrations were well below the values observed on the computer printout.

The raw count as printed out on the DAS was hand-calculated for a number of data points and compared to the calculated values as printed out on the computer printer. No large disagreements were observed. The cause of the apparent difference between grab and continuous radon samples has not yet been determined. The quick-connect valve on the EDA flasks is currently under suspicion. The situation was discussed with the Technical Project Officer during several phone conversations, and it was agreed to discontinue further efforts with these flasks until they could be tested at USBM/SRC.

H. Direct Measurement of Radon Flux

To determine whether the expected high concentration of radon bulkheaded into a confined space might influence the radon concentration in the rock immediately outside and adjacent to the bulkheads (a by-pass as it were), a series of flux canister collars was sealed onto the ribs. Collars were initially sited as points roughly 30, 60,

TABLE 14

EDA Flask Sampling at Detector 52, Radon Concentrations in pCi/l

Date:	2/24	2/26	3/02	3/10
Concentration	186	308	479	238
	212	297	499	236
	209	346	465	221
	209	346	484	202
Average Reading	204	324	482	224
Printout	550	517	647	532

120 cm out from the expected bulkhead position, and allowed the determination of representative radon flux unenhanced by the additional confinement due to bulkheading. The technique used to measure radon flux (1) had been found to be practical and reasonably accurate in monitoring changes in flux at individual locations over a period of time.

Radon flux was determined by the method of R. J. Countess(2). The method is based on the fact that radon is spontaneously adsorbed onto the surface at room temperature in amounts that are proportional to the concentration of the gas in the ambient air. By exposing a known quantity of charcoal to radon-containing air for a fixed period of time, the amount of radon accumulated by the charcoal is thus a measure of the radon existing in the air. The adsorbed radon is allowed to stand for about three hours to allow the short-lived gamma-emitting daughters, ^{214}Pb and ^{214}Bi, to grow into equilibrium, after which a gamma assay is made from which the parent ^{222}Rn concentration can be calculated. By knowing the time during which radon was collected and the surface area of the rock over which the flux samples was taken, the flux can be calculated in terms of Ci/cm^2-sec. The metal collars made from tuna cans were cemented to the rock with a waterproof epoxy sealant to restrict the region of flux under investigation. Each collar (diameter 8.3 cm; area 54 cm^2) was numbered and designated "1" or "2" for bulkhead 1 or 2, "L" or "R" for left or right rib, "U" or "L" for upper or lower level, and "1", "2", or "4" for distance from the bulkhead. Attention quickly focused on those sites located 30 to 60 cm removed from the bulkhead, and further sampling of sites 120 cm away was discontinued.

Canister sites positioned on the bulkheads themselves were designated "B" for bulkhead, "1" or "2" for bulkhead identification (B-1 being the bulkhead constructed with the EPDM membrane and B-2 the bulkhead containing Aquafas), and "L", "C" or "R" for location on the bulkhead (left, center, or right as the bulkhead was faced). The canisters of activated carbon were obtained from a commercial supplier of occupational gas masks (MSA, No. 459315; 6.3 cm diameter). They were brought to the site in sealed polyethylene bags. At a recorded time, the canister was removed from the bag and placed in the collar. A metal lid was taped over the opening of the collar to prevent free circulation of the ambient mine air into the sampling chamber. After one hour the canister was removed and returned to the bag for a three hour period to allow growth of the short-lived daughters to equilibrium with the parent radon. Then the gamma activity of each canister was measured.

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(1) Lindsay, D.B., J.E. Oberholtzer, C.H. Summers. Sealant Tests to Control Radon Emanation in a Uranium Mine. Arthur D. Little, Inc. report to U.S. Bureau of Mines, Contract J0199041. 1982, 89 pp.

(2) Countess, Richard J., Measurement of ^{222}Rn Flux with Charcoal Canisters. Radon Workshop, 1977 (HASL-325), pp 149-54.

A 7.5 cm by 7.5 cm NaI (Tl) scintillation counter was positioned inside a 7.5 cm-thick lead brick shield. It was calibrated before each measurement for six seconds with a standard 1 μCi ^{137}Cs source. Two-minute background counts for a clean canister-plus-scintillation system were also taken. Radon daughter gamma activity from each sample charcoal canister was counted for five minutes.

Through the courtesy of A. George of US DOE Environmental Measurement Laboratories in New York City, our charcoal canister radon collection and gamma-counting system was calibrated, using a radium-bearing (and radon-emitting) concrete slab as a standard source of ^{214}Bi and ^{214}Pb gamma radiation. The calibration coefficient (3.3×10^{11} counts/minute) is unique to the system used.

The radon flux was calculated by the following method:

$$J\ (\text{Ci/cm}^2\text{-sec}) = \frac{\text{net counts (min}^{-1}\text{) x decay correction}}{\text{area sampled (cm}^2\text{) x exposure time (sec x calibration coefficient (min}^{-1}\text{)}}$$

$$= \frac{\text{net counts (min}^{-1}\text{)}\ \frac{1}{(0.97)}}{(54)\ (60 \times 60)\ (3.3 \times 10^{11})} = \text{net counts (min}^{-1}\text{)}(1.61 \times 10^{-17})$$

where:

- area of collar = 54 cm^2
- one hour in seconds = 60 min x 60 sec
- decay correction for 1 hour exposure + 3 hours delay + 5 min. counting = 1/0.97
- calibration coefficient = 3.3×10^{11} counts/min

The above flux measurement procedure was followed until February 11, 1982, after which canister backgrounds were counted for five minutes rather than two.

The data are listed in Tables 7, 15, 16, and 17. The data in Table 16 would indicate no significant difference (within one standard deviation) between average fluxes determined before the construction of bulkheads (pre-bulkhead data) and average fluxes determined after construction of bulkheads, but prior to sealing surfaces for a distance of one meter out from each bulkhead. We may then say there is no clear evidence to support the conjecture that construction of a radon restraint will cause an increase in radon flux in the area immediately near the restraint. The third set of average fluxes in the same table (Table 16) indicate that sealing the area immediately near the restraint is clearly effective in the reduction of flux in the sealed area.

TABLE 15

Flux Data*, Sites on Bulkheads, in Units of Ci cm^{-2} sec^{-1} x 10^{-14}

Date	Site B-1L	B-1C	B-1R	B-2L	B-2C	B-2R	Barometric Pressure, mm Hg	Concentrations Behind Bulkheads, pCi/l B1	B2
1/26	1.62	2.10	2.11	3.42	2.46	3.29	612(o)	27,800	28,300
1/27	1.22	0.99	1.20	NA	NA	NA	612(+)	29,800	32,400
1/28	2.28	1.74	1.63	2.07	1.28	1.64	606(o)	31,500	31,700
1/29	0.08	0.43	0.56	0.62	0.44	0.40	603(o)	35,200	36,000
2/1	0.97	0.81	0.24	0.67	0.24	0.57	609(+)	29,300	29,000
2/4	0.80	NA	1.28	0.61	0.67	0.60	601(o)	34,100	36,400
2/8	1.36	0.35	0.74	0.94	0.88	1.58	606(o)	32,400	32,300
2/11	0.38	0.12	0.10	0.28	0.56	0.10	608(o)	31,300	32,600
2/16	1.20	1.22	0.84	1.31	1.14	0.77	613(0)	24,900	24,900
2/18	0.37	0.06	NA	0.45	0.33	0.17	614(+)	27,900	26,900
2/25	NA	0.42	0.08	0.53	0.53	0.25	614(o)	25,100	23,700
3/11	0.85	1.12	0.61	0.83	0.76	0.56	613(-)	*NA	NA
3/16	0.34	0.67	0.42	0.40	0.52	0.27	609(o)	32,700	35,800
3/24	0.35	0.09	0.22	0.54	0.52	0.02	617(o)	30,200	33,600

Baromatric pressure change during three hours preceding sampling: (o) = Steady, (+) = Rising, (-) = Falling

*Bulkhead area under positive pressure.

NA - Not Available

TABLE 16

FLUX DATA SUMMARIES

	1LL1	1LL2	1LU2	1RL2	1RU1	2LL1	2LU1	2LU2	2RU1	2RU2
1) Ave, pre-bulkhead	7.94	11.2	10.4	16.3	14.3	5.11	3.45	6.19	4.41	4.13
σ, pre-bulkhead	3.86	3.35	3.06	8.57	4.50	3.63	0.70	6.25	2.46	3.26
2) Ave, passive restraint	6.92	10.4	7.93	16.5	12.9	21.0†	7.15	6.25	4.43	6.84
σ, passive restraint	5.09	5.59	4.65	8.42	5.43	23.8†	6.76	4.51	3.05	8.29
3) Ave, sealed period	0.61	0.71	NA	0.61	0.42	0.62	0.80	0.70	0.91	0.76
σ, sealed period	0.32	0.49	NA	0.22	0.28	0.20	0.40	0.21	0.55	0.55

Average and 1σ standard deviation of mean for calculated radon flux on ribs during three time periods:

1) pre-bulkhead construction
2) post construction but pre-sealing ribs
3) post rib-sealing

† ave 14.7 } without 77.8 value
† σ 13.7 }

NA - Not Available

TABLE 17

"Blank" Flux Data, Units in Ci cm^{-2} sec^{-1} x 10^{-14}

Date:	3/23	3/24	3/25
	0.82	0.41	0.65
	0.49	0.51	0.58

Average = 0.58 $\pm$ 0.32 (2σ)

0.58 + 0.32 = 0.90 x 10^{-14} Ci cm^{-2} sec^{-1}

The 2σ value on several sets of sample was calculated to also be $\pm$ 0.32 therefore, any sample whose calculated flux is less than 1.22 x 10^{-14} Ci cm^{-2} sec^{-1} cannot be differentiated from a blank.

Background counts were much higher than desirable (~900 counts per minute), probably due to the surface buildings at the mine being located over, and adjacent to, spoils areas emitting gamma radiation from radon daughters in equilibrium with residual radium.

I. Air Direction Reversal

Reversal of air direction in the only two upcast fans in the LaSal Mine had been under consideration by mine management for some time, but was intentionally delayed so as not to interfere with the experimental bulkhead project. A test of the effect of total mine positive-pressure ventilation was scheduled for March 13th, a date agreeable to both UCC and Arthur D. Little, Inc.

The fan exhausting air through the borehole adjacent to the test site consisted of two 30 hp motors, each separately operated, but set electrically such that a maximum delay of three minutes between starting the two motors was permitted. The time and timing of fan reversal was discussed with the lead electrician, and a schedule agreed to. At 0830 the air direction was reversed. No observable changes were detected at either bulkhead. At 1345 the air direction was again reversed, returning it to the upcast direction, and again no observable changes were detected at either bulkhead. No evidence of any problem associated with the fan reversal was observed. Data from several parameters monitored during this time are given in Table 18. A plot (Figure 15) of radon concentration in drift F air before, during, and immediately after the air direction reversal shows the reversal nicely.

J. Use of the Portable Radiation Survey Meter

A portable radiation survey meter (Cutie Pie - Model CP-5, Technical Associates, Inc.) was used to monitor gamma activity, primarily in the radon-sorbing charcoal behind bulkhead B-2. This instrument consists in part of an air ionization chamber with a thin mylar window which can be covered by a plastic cap (eliminating alpha and soft beta penetration). The instrument was not designed for use in an atmosphere of alpha-emitting radioactive gas such as radon. Activity values thought to be due primarily to gamma radiation became suspect when levels well above those permissible for continuous personal exposure (100 mR/week, or an average limit of 2.5 mR/hour) were continuously observed, not only at the bulkhead near the charcoal drums, but throughout the test area. The instrument was taken above ground and to a low-radon area whereupon the reading decreased slowly from 5 mR/hr to <0.1 mR/hr overnight. The instrument was packaged in a double-walled polyethylene bag, taken back into the test site where the following values were observed:

DAS Laboratory	0.5 mR/hr
in front of B-2	1.1 mR/hr

TABLE 18

Observed Data During Air Direction Reversal

Time/Parameter	Linear + Velocity	[Rn] B-1	Behind B-2	Differential Pressure Reading	[Rn], Interstitials 150cm	[Rn], Interstitials 450cm	[Rn], Detectors Det. 52	[Rn], Detectors Det. 48
0700	876	30,300	34,200	498	6,725	56,700	616	564
0800	874	30,600	34,200	494	6,736	56,400	601	555
1000	2377	30,200	33,800	490	6,195	42,000	133	219
1100	2523	29,900	33,600	495	5,956	45,600	61	139
1200	2227	30,100	33,400	499	6,011	50,700	36	123
1300	2354	30,400	33,400	501	7,500	61,900	30	155
1400	1870	30,900	33,600	507	12,200	88,400	93	201
1500	938	31,500	33,600	512	25,900	147,100	665	658
1600	946	32,100	33,500	508	29,000	153,600	1069	1058
1700	975	32,800	33,500	507	29,100	151,200	1222	1150
1800	936	33,400	33,600	505	27,700	145,600	1270	1217
1900	963	33,800	33,800	502	24,400	134,500	1259	1232
0000	970	33,600	34,500	498	10,600	81,300	1201	1157
1800	968	33,100	34,400	495	8,970	74,800	1140	1089

1) Linear velocity readings indicate the large change occurring when the air direction was reversed at 0830, then returned to its original direction at 1345 with an increased flow due to an air curtain being displaced by the air reversal. This effect is also readily observed in the large ambient [Rn] increase in Detectors 49 and 52.

2) An increase in pressure behind the bulkheads relative to the pressure outside the bulkheads with a time lag of about four hours is observed. Note that no real change in the large volume behind the bulkheads was observed, but concentrations in the rock (both interstitials) increased greatly.

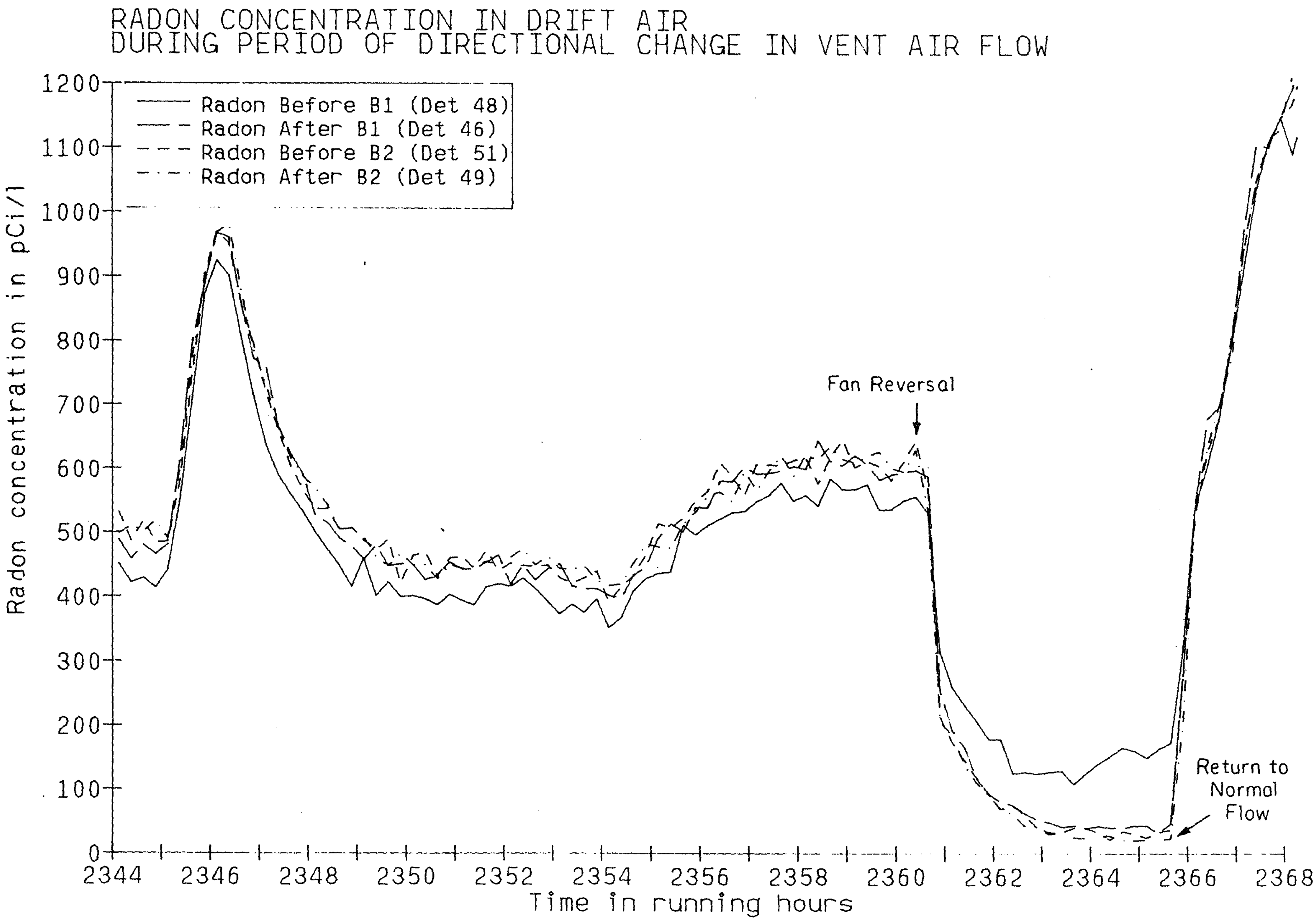


FIGURE 15

RADON CONCENTRATION IN DRIFT AIR
DURING PERIOD OF DIRECTIONAL CHANGE IN VENT AIR FLOW

Upon removal from the polyethylene bag, the instrument immediately began to show increased mR readings. It appears that modifications will be necessary if this type of instrument is to be used in a radon-polluted atmosphere.

K. Air Cleaner

Measurements of WL in the instrument laboratory (in which the two DAS units and the microcomputer were installed) had consistently shown levels that were close to - or occasionally above - the recommended ceiling level of 1.0. Inasmuch as the ventilation air in this part of the mine was known to be waste air and was being drawn to an upcast shaft near the test site, we knew that high WL values were to be expected there. The situation seemed ideally suited to the application of a local radon-daughter-removal system to the air being used to ventilate the instrument room. We therefore arranged with a local heating-and-ventilating contractor in the Boston area, Glover Sheet Metal Company of Newton, Massachusetts, to construct a small air filtration system for this purpose.

The principles of the design were those recommended to USBM by us in our final report for Contract No. J0265011 "Engineering Evaluation of Radon Daughter Removal Techniques," April 1978. The accompanying sketch, Figure 16, shows the general plan of the system. A small centrifugal fan, powered by a 117 vac electric motor, was arranged to draw air through a rectangular housing containing three air filter cartridges. The filters measure 61 cm x 61 cm in area, and were set up in series, in air-tight gasketed frames. The first filter was a simple impingement type fiberglass roughing filter, 25 cm thick. The second filter was an intermediate filter 150 cm thick, rated 85% NBS Dust-spot and supplied by American Air Filter Company. The third and final filter was a "95% DOP Test" filter, supplied by Farr Company, Los Angeles, CA., and was also 150 cm thick. The system was designed to deliver 8.5 m^3/min of air across the combined pressure drop of the filters. A manually adjustable throttling vane was inserted (as shown in the sketch) to allow adjustment of the output to a suitable flow-rate for ventilation of the instrument room. The unit was designed to allow easy access to the filter cartridges for routine replacement as they became loaded with collected dust. The purpose of the three-element design was, it will be recalled, to provide efficient removal of respirable dusts (by the 95% DOP unit), while extending the useful life of this relatively costly component by pre-filtering the air successively through the less expensive "roughing" and "intermediate" cells. The entire unit measured 61 cm x 61 cm x 142 cm and weighed 77kg.

Results of the use of this WL-reduction system were highly gratifying. Operation of the air filtration unit began on February 10, 1982. (Julian day 041).

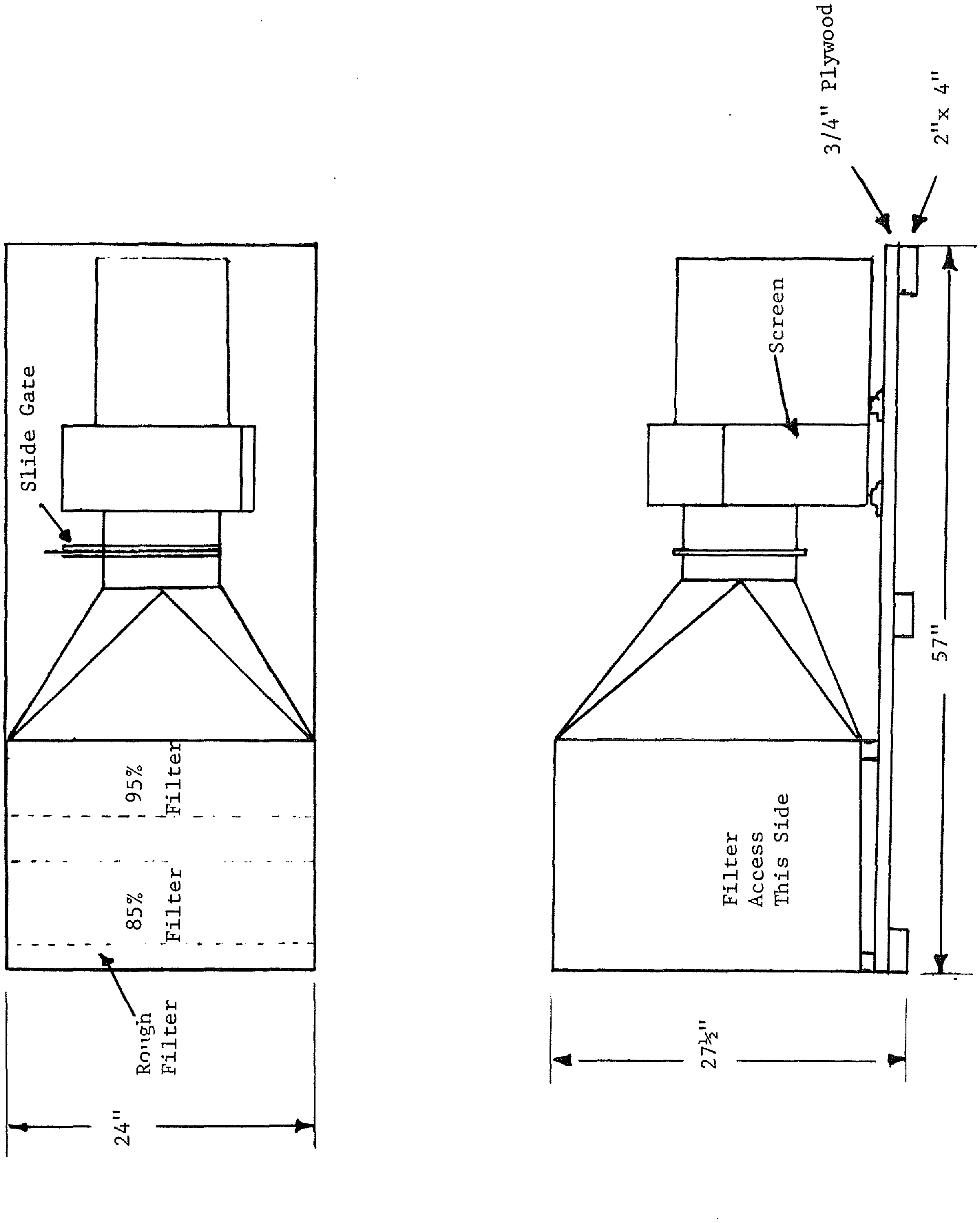


FIGURE 16

Air Filter for Radon Daughter Removal

At the time the cleaner was installed the Working Level (WL) in the room was 1.11. After six hours of operation the WL had been reduced to 0.39. The fan pushing air into the room (through a furnace filter) was shut off when the air cleaner was turned on, and was used only intermittently afterward. Table 19 shows the effect of using the air cleaning system.

TABLE 19

OBSERVATIONS OF USE OF A PORTABLE AIR CLEANER

Julian Date	Time	Observed WL
041	0800(+)	1.11
041	1400(o)	0.39
042	0800(+)	1.01
042	1400(o)	0.14
047	0900(+)	0.78
048	0900(†)	0.19
050	1400(†)	0.03
053	0800(†)	0.07
156	1200(o)	0.02
057	0800(+)	0.14
057	1100(o)	0.03
060	0800(+)	0.14
061	0800(†)	0.10
062	0800(o)	0.11
063	1600(oo)	0.11
064	0800(oo)	0.11
067	0800(oo)	0.15
072	0800(oo)	0.14
074	0800(+)	3.7
075	0800(o)	0.17
076	0900(+)	0.49
076	1200(o)	0.30
077	0800(+)	0.65
077	1100(o)	0.33
078	0800(oo)	0.11
081	0800(+)	0.40
087	1200(o)	0.31
082	0900(+)	0.42
082	1300(o)	0.38
083	0900(+)	0.50
083	1300(†)	0.39
084	1100(†)	0.34
085	0800(o)	0.22

end of experiment

(+) = turned on

(†) = left on

(o) = turned off

(oo) = left off

VI. CONCLUSIONS AND RECOMMENDATIONS

The principal conclusion derived from this study is that, by using selected modern construction materials which are readily available from major commercial suppliers, inexpensive, air-restraining bulkheads can be constructed which will effectively prevent the escape of radon-polluted air from inactive workings into the main ventilation air supply of an underground uranium mine. Our tests of two such novel bulkheading systems, both of which incorporated conventional timber framing and could be assembled and installed by semi-skilled workers in a few hours' time, showed that all the essential requirements of practicality, durability and radon-impermeability were satisfied.

The condition under which the field test was conducted were fairly typical of underground mining operations, such that the test bulkheads were subjected to repeated ground movements caused by blasting in nearby headings, as well as air pressure disturbances ranging from ordinary meteorological effects to abrupt cessation and even reversal of direction of the primary ventilation system, one of whose major exhaust (and alternately, supply) fans was located near the test site. Conventional bulkheads are usually leaky, and are apt to become more so as a result of brittle fracture of the sealant membrane or poor adhesion to the rock surface. The materials we used were designed to avoid these limitations by being tough, resilient and having excellent adhesion to wood, and to either dry or wet rock. We believe that the results of this program confirm our expectation that these new materials and methods of bulkhead construction represent an important advance in the technology of radon control in underground mines.

A number of other conclusions that were reached in this study are also worth mentioning. One of these concerns the need for sealing the surface of the drift for a distance of a meter or so on either side of the bulkhead to prevent leakage of the highly radon-polluted air through the porous rock immediately adjacent to the bulkhead under the influence of an adverse air pressure differential. While such leakage undoubtedly occurs to some extent, the amount of radon escaping by this route from a trapped volume whose radon concentration is at least as high as what we experienced (30,000 pCi/1) is not enough to warrant the use of a wall sealant, provided, of course, that all cracks, fissures and holes in the rock are sealed to prevent major convective leakage. Furthermore, although we took care to select bulkhead-sealing materials that had quite low permeability to radon, so that leakage of radon by permeation across the membrane was insignificantly low, it is our conclusion that the most important advantage offered by the selected materials was their ability to prevent gross leakage of air by virtue of their excellent adhesion and resistance to tearing or brittle fracture.

The use of a "bleeder-pipe" to relieve any excess air pressure behind the bulkheads in the event of a rapid fall of barometric pressure outside the mine or an upset of ventilation systems within the mine was planned on the assumption that a totally sealed bulkhead would probably leak slightly under such conditions. Although our tests showed no measurable leakage through the un-vented bulkheads, we proceeded to carry out the tests, using first an open bleeder pipe, and then a fan-assisted vent. The use of the bleeder pipe, especially with the auxiliary exhaust fan which operated automatically in response to a signal from a differential pressure monitor, was effective in preventing the ocurrence of adverse pressure differentials across the bulkheads, but since no measurable leakage had occurred, even without the bleeder, we were unable to assess its value in preventing such leakage.

The use of a charcoal trap to adsorb radon that would otherwise escape into the exhaust air system via the open bleeder pipe was found to be highly effective. The very high (in excess of 30,000 pCi/1) radon concentration in the exhaust air was reduced to about 65 pCi/1 after passage through two consecutive (91 kg) charcoal filters. The servo-controlled fan, which limited the exhaust cycle to periods when the pressure behind the bulkhead would normally have been higher than that outside it, greatly extended the useful life of the charcoal trap system. As a result, no radon breakthrough was observed, even from the first of the two traps, during the period of the test. The small amount of radon that did find its way through both traps was probably due to uncorrected channeling of the air-flow rather than to saturation of the charcoal.

In conclusion, we strongly recommend the adoption of materials and methods of bulkhead construction such as those we selected and tested in this program. The costs of these systems for both labor and materials are modest in comparison to other means of controlling radon pollution of mine air, and, especially for older mines in which the existence of large inactive areas contributes a large part of the radon pollution problem, the benefit of an effective bulkheading program can be substantial.

Some of the positive results we recorded have suggested the possibility that even more effective and efficient systems could be designed as auxiliaries to one or the other of the recommended bulkhead systems. In particular, we are encouraged to believe that the charcoal-trap system we devised for removal of radon from the small amount of highly polluted air exhausted from behind the bulkheads can be made considerably more efficient through improved design of the trap and selection of the charcoal sorbent. A system designed to minimize pressure drop, while permitting little or no channeling, should be developed so as to allow any desired air throughput volume and radon hold-up time. Such a system would give maximum flexibility and efficiency for a wide range of practical applications in the operation of an effective bulkheading program.

APPENDIX A-1

A-1 RADON FLUX DETERMINATIONS

A. Principle of Method

This is a hand-sampling technique for collecting and measuring the flux (J) of radon coming out of the surface of the rock. Radon gas is collected and trapped on a charcoal absorber and allowed to decay for three hours in order to allow for growth and equilibration of radon daughter activity. The charcoal used in this equipment is contained in a standard respirator cartidge such as Mine Safety Appliances Part No. 459315, Chemical Cartridge GMA- Organic Vapors Gas Mask Canister. A gamma count is taken on the residuum in the charcoal using a 7.5 cm x 7.5 cm NaI:Tl scintillation counter. The count can then be converted to radon flux by means of the formula given below.

B. Installation

1. Obtain the required number of 6 1/2 oz tuna or cat food cans (which are about 4 x 10 cm in size), remove and save both lids and clean the cans thoroughly.

2. Select the sites to be sampled. Sites must be relatively even or the collars used will not seal to the rock effectively, and should be about 15 x 15 cm in size.

3. Cement each metal can collar in place using a two-part epoxy adhesive such as Marine-Tex.*

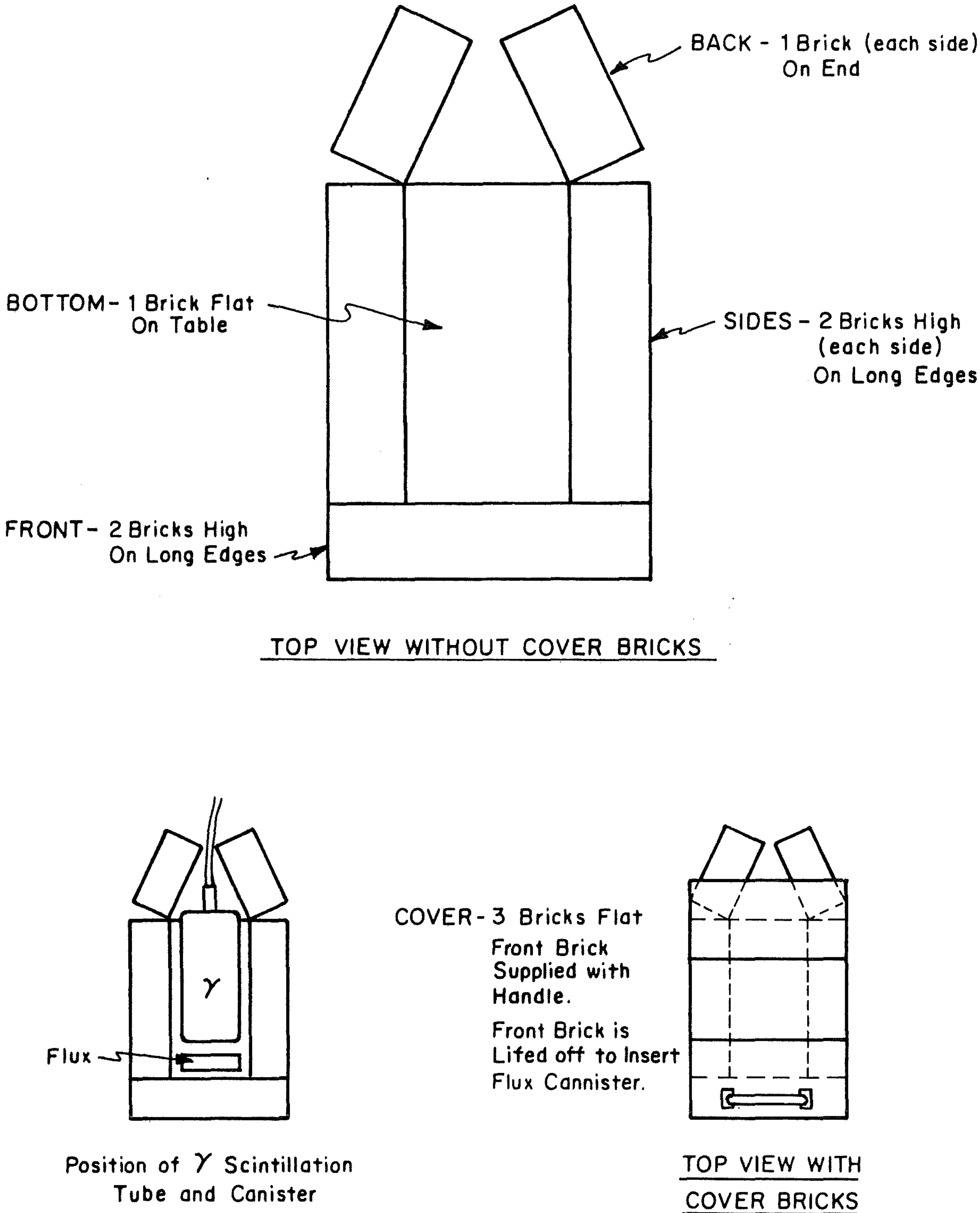
C. Calibration

1. Set up the gamma scintillation detector inside a chamber made of 12 standard lead bricks as shown in Figure 17. Leave space at the end of the detector for the charcoal canister. The detector is a 7.5 cm x 7.5 cm NaI:Tl scintillation crystal mounted on an end-window photomultiplier tube (Harshaw Model 8S).

2. Determine the correct operating voltage for the photomultiplier used by centering a ^{137}Cs source on the face of the scintillation crystal, and plotting counts per unit time versus applied voltage. A plateau will quickly be found wherein the counts are independent of the applied voltage. Above and below this plateau the counts will be quite dependent on voltage. The correct operating voltage is somewhere near the center of this plateau.

3. Use the 1μCi ^{137}Cs calibration source mounted approximately 2 cm away from the front face of the scintillation detector and on its

*Product of Travaco Laboratories, Inc., 345 Eastern Ave., Chelsea,MA 02150.



Note: All Bricks are 2" x 4" x 8" LEAD BRICKS, 12 Required.

FIGURE 17 - Lead Cave for Gamma Counting

center line. Count for 0.1 minute. Record the results in the notebook: proper operating voltage, and counts per 0.1 minute for the ^{137}Cs standard. The count/0.1 minute figure will be used throughout the experiment when checking the operation of the equipment. Small deviations from the "standard" count may indicate that the scintillation detector has been moved slightly, relative to the ^{137}Cs source, since the previous measurement. If so, correct the placement so that a "standard" count is obtained. Remove the ^{137}Cs source. Close up the lead brick chamber and count for up to five minutes to check background. If the background is high, look for "leaks" in the lead brick shielding, nearby sources of radioactivity or radioactive ore dust, etc., inside the chamber. Backgrounds will vary with location. Low backgrounds are more desirable.

D. Operation

1. After checking proper operation of the equipment with the ^{137}Cs source, center a flux canister in the chamber with the black side facing the scintillation counter. Close the chamber and count for at least two (but ideally for five) minutes. Record the count and identification number of the flux can, and place it in a closed polyethylene bag for storage. Repeat for each canister to be used that day.

2. Take the bagged canisters to the site, remove from bags, and place one charcoal canister in each sampling collar attached to the rock, black side facing the rock. Cover the can with a can lid and tape it firmly in place to prevent free circulation of air. Record the location, canister number, and time of placement (to nearest 0.1 minute).

3. Sixty minutes later, collect the canisters; replace them in individual polyethylene bags; close the bags; record the time of removal, canister number, and site as above.

4. Three hours later begin scintillation counts of the canister, as in above, for 5.0 minutes each. Record the count, canister number and time at which count was made, again to the nearest 0.1 minute. A sample data sheet is shown in Figure 18.

5. Calculate radon flux in Ci cm^{-2}sec^{-1} by the following formula below

$$\frac{[(\text{Observed Sample Counts/min}) - (\text{Background Counts/min})]\ (F)}{(54)\ (3.3 \times 10^{11})\ (60 \times 60)} = J \text{ in Ci cm}^{-2}\text{sec}^{-1}$$

(54) Area Sampled-Cm^2; (3.3 x 10^{11}) Calibration Factor for Given Set-up; (60 Min. Exposure Time; x 60) Sec/min

*New England Nuclear Corporation Model NES 1315 or equivalent.

Canister I.D.	Background ct. per min.	Sampling site	Time on	Time off	Time counted	Gross count	Net count	Flux
F	670	1LL1	1027	1127	1427	4123	3453	5.5×10^{-14} ci cm^{-2} sec^{-1}

FIGURE 18 - Sample Data Sheet
Flux Calculations

where F = 1.0309 if canisters are counted three hours after removal from the collars, and 1.0417 if canisters are counted four hours after removal. The 3.3×10^{11} factor is unique to the system used here. Each system factor would have to be determined using a standard source such as is used by A. George of U.S. DOE Environmental Measurement Laboratories N.Y.C.

6. Desorb residual radon from the charcoal by drawing clean warm air (about 60°C) through the canisters for about an hour. Vent air to the outside. Cool the canisters and seal them immediately in polyethylene bags for storage and reuse. The canisters can be used many times before their residual radioactivity becomes high enough to interfere with accuracy of measurement of new radon samples. A simple thermal desorption device, illustrated in Figure 19 can be put together easily from a small plywood box, electric hair dryer and a small exhaust fan. Such a device can process many canisters at once.

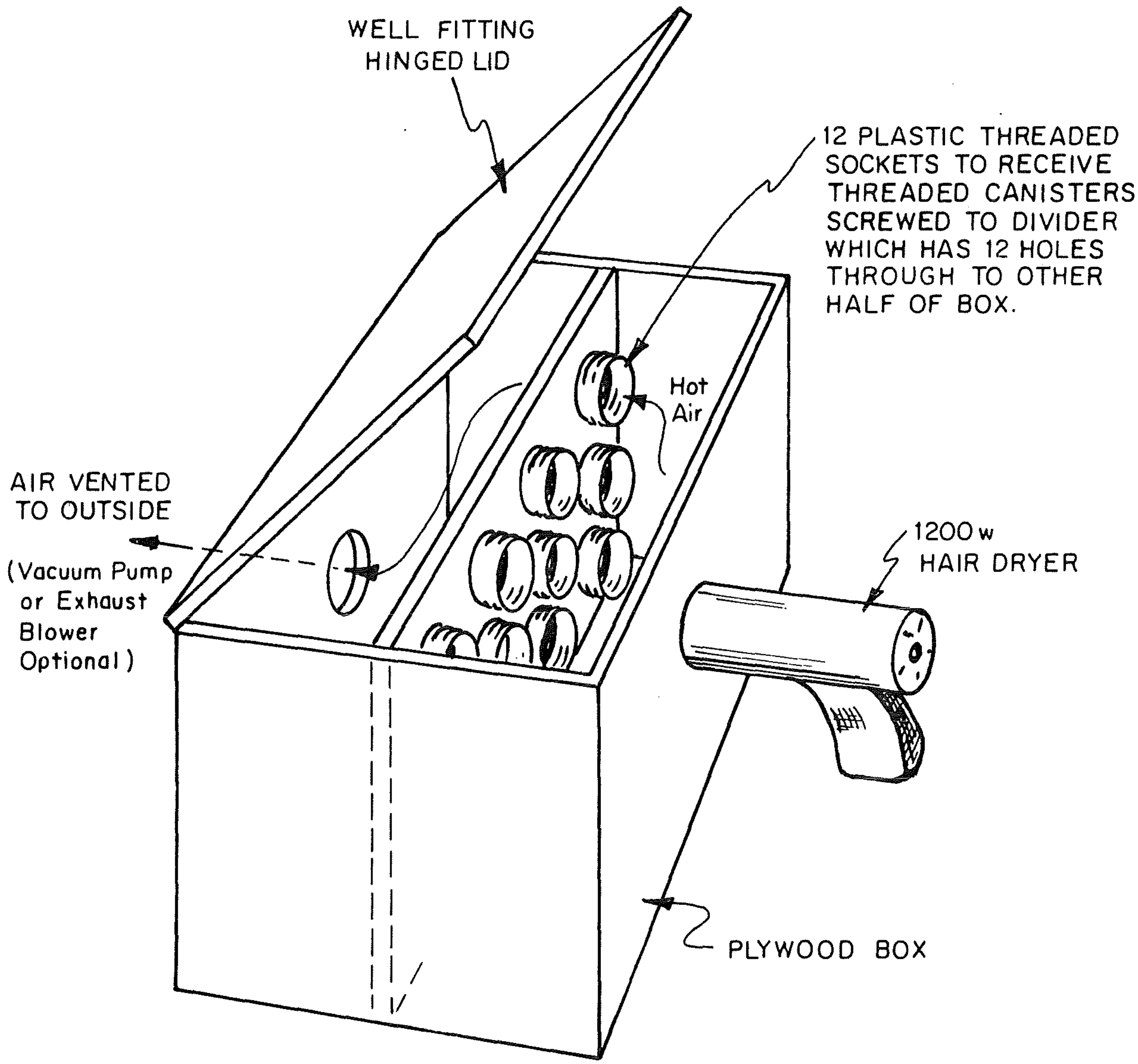


FIGURE 19

THERMAL Rn DESORPTION DEVICE FOR FLUX CANISTERS

APPENDIX A-2

Union Carbide Corporation, Metals Division agrees to indemnify Arthur D. Little, Inc. against any injury or harm to the LaSal Mine and to UCC employees or others, arising from the existence and/or use of either or both of the bulkheads or the drums of charcoal situated behind one of the bulkheads located in the LaSal Mine, and constructed by employees of Arthur D. Little, Inc.

Reference:

Evaluation of Bulkheads for Radon Control a Technical Proposal Submitted to U.C. Dept of the Interior, Bureau of Mines by Arthur D. Little, Inc. of Cambridge, Massachusetts, March 7, 1980

B. A. Greene UCC

R. F. Barnett UCC

G. L. Sampson UCC

C. H. Summers for A. D. Little, Inc

Cliff Summers Arthur D. Little

bcc: C. Summers

APPENDIX A-3

Arthur D. Little, Inc. ACORN PARK · CAMBRIDGE, MA 02140 · (617) 864-5770 · TELEX 921436

August 26, 1981

Mr. Bruce Green
Mine Superintendent
LaSal Mine
Union Carbide Corp.
LaSal, Utah

Dear Mr. Green:

At the suggestion of Niels Haubold, with whom I talked by telephone yesterday afternoon, I am writing to tell you about a project we are conducting on behalf of U.S. Bureau of Mines, Spokane Mining Research Center, and for which we need the cooperation of a commercial mining company for a period of about five to six months beginning as soon as possible. Mr. Haubold suggested that a test site in either the LaSal or the King Solomon Mine might be made available to us, and that I should let you and Ron Evans know what our needs are, so that we could work something out with one or the other of you.

What the Bureau has asked us to do is to select what we believe to be two of the best available combinations of materials for construction and sealing of bulkheads for confinement of highly radon-polluted air in inactive unventilated portions of underground uranium mines. We are then to erect one bulkhead of each type in a suitable place in an operating mine, and proceed to test the effectiveness of each bulkhead in preventing escape of radon (and daughter products) into the ventilation air in the adjoining haulageway. In order to allow our assessment of the effectiveness of the experimental bulkhead materials to be independent of any major uncontrolled variables, we need to have an isolated stope or heading of at least 100,000 cubic feet open volume which is accessible through not more than two entries, both of which would be suitable sites for bulkheading. (If only a single entry exists, we would need two such stopes to permit the two bulkheads to be tested simultaneously, a modification to the original work statement which will allow the field test to be completed in the shortest possible time.) The test stope ought to be essentially air tight, once the bulkhead is in place, to permit maintenance of a slight negative pressure within it by exhausting no more than 100 cfm of air continuously through a "bleeder" pipe.

Radium content of the ground surrounding the bulkheaded volume should be sufficient to produce an equilibrium radon concentration in the stagnant confined air of about 100,000 pCi/L. Radon concentration in the haulageway air at the face of the bulkhead ought to be less than 100 pCi/L. We would hope to be able to bring clean ventilation air to the site by means of a secondary vent tube directly from a primary vent shaft if there is any doubt about maintaining the cleanliness of the haulageway air during the period of the test.

We expect to be using two of the Bureau's Data Acquisition Systems to monitor radon, WL, air flow, temperature, relative humidity and barometric pressure around the test bulkheads. We will therefore need a supply of 110 VAC and 220 VAC at each bulkhead, and a suitable location, either underground or in a surface building for the DAS and associated microcomputer equipment which our field engineers will be using. We would expect to compensate Union Carbide for any labor and materials you supply to us in helping to set up the test and to return the site to a satisfactory condition when the test is finished.

At Atlas Minerals' Pandora Mine, where we conducted a test of wall-sealant last year, we were given space for our DAS equipment in a surface building near the mine entry. Since access to that mine is by an inclined roadway, we used our own diesel powered four-wheel drive station wagon for transportation to and from the test site in the mine. This proved convenient and satisfactory to everyone concerned. Since we still have the vehicle (in storage at Grand Junction) we would be able to use it in a similar situation for this new project if that opportunity should arise.

The design of the bulkheads will include a small vent pipe which will have to be connected to an existing waste-air exhaust system. We would expect to bear the cost of making the necessary ventilation connections, of course, as well as constructing the bulkheads themselves. The bulkhead vent bleeder will be operated for a period as a passive vent, and then for a period with active exhaust by a small fan, and finally (conditions permitting) with an experimental charcoal trap to arrest radon and prevent it from escaping to the environment.

The object of all this exercise is, as I have indicated, to try to find an improved bulkheading system for confining and controlling radon-polluted air in inactive closed-off portions of underground mines. It is well known that conventional bulkheads often fail to contain the radon-rich air that exists in sealed-off stopes and that this failure can have damaging effects on the air quality downstream of the bulkhead. The Bureau believes that improved bulkhead design, including active air-pressure gradient control, can do much to correct this condition. We realize that Union Carbide and other mining companies have experimented with many different materials and designs of air-restraining bulkheads for radon control over the past two or three decades, and that you probably have much unpublished information about what works and what doesn't. We have no illusions about making a great breakthrough in bulkhead technology, but if we can at least confirm and document on the

Arthur D. Little, Inc.

August 26, 1981

Mr. Bruce Green
Union Carbide Corp.

Bureau's behalf what may now be known only to isolated portions of the industry, we believe we will have performed a useful service.

Our choice of materials and designs for the test is not yet confirmed. At least one of the bulkheads will be built on conventional timber framing, probably with expanded metal lath as a backing for a surface coat of a non-flammable inorganic grout such as magnesium oxysulfate. To avoid the familiar problem of air leakage developing where the bulkhead meets the walls of the drift, we are looking for a bedding material that will adhere to rock (including wet rock) and that will retain a degree of resiliency that will allow it to resist the effect of ground movement and the shock of blasting operations.

If there is a possibility that you could find a suitable site in your mine in which we could conduct this test, we would like to set up a date for our field engineer, Clifford Summers, and me to visit the mine and talk with you about it.

I shall enclose a copy of the Statement of Work, pp. 2-5 of our contract with USBM, which states in some detail what we will be trying to do. You will notice that the schedule described in the contract calls for a sequential testing of two systems in the same site. John Franklin, who is our our Project Officer on this job, has said that he would prefer to test the two systems simultaneously, to save time and cost, as I have indicated earlier in this letter.

I will call you next week to make arrangements for a visit to the mine if that will be convenient for you.

Very truly yours,

Donald B. Lindsay

/laf
enclosure

cc: Roger Swindle
Union Carbide Corp.

Niels Haubold
Union Carbide Corp.

bcc: C. Summers

APPENDIX A-4

Arthur D. Little, Inc. ACORN PARK · CAMBRIDGE, MA 02140 · (617) 864-5770 · TELEX 921436

August 26, 1981

Mr. Niels Haubold
Manager of Uravan Mining
Union Carbide Corp.
Mine and Metals Division
Grand Junction, Colorado

Dear Mr. Haubold:

Enclosed are copies of letters (essentially identical) which I have sent to Bruce Green and Ron Evans at the LaSal and King Solomon Mines, as you suggested.

Thank you very much for your willingness to help us with this project. I trust that after we have had a chance to visit one or both of the mines and have talked with the people there, we will find the site we need for our test. I will keep you informed of our progress, and will try to stop by your office in Grand Junction when we are in town.

Very truly yours,

Donald B. Lindsay

/laf

enclosures

CAMBRIDGE, MASSACHUSETTS
ATHENS BRUSSELS LONDON MADRID PARIS RIO DE JANEIRO SAN FRANCISCO SÃO PAULO TOKYO TORONTO WASHINGTON WIESBADEN