

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control
National Institute for Occupational Safety and Health

NIOOSH

A Recommended Standard for Occupational Exposure to....

RADON PROGENY in UNDERGROUND MINES



**CRITERIA FOR A RECOMMENDED STANDARD...
OCCUPATIONAL EXPOSURE TO RADON PROGENY IN
UNDERGROUND MINES**

**U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTERS FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
DIVISION OF STANDARDS DEVELOPMENT AND TECHNOLOGY TRANSFER**

October 1987

DISCLAIMER

Mention of the name of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

DHHS (NIOSH) Publication No. 88-101

ii

FOREWORD

As Director of the National Institute for Occupational Safety and Health (NIOSH), I am accustomed to making decisions on difficult issues, but few issues have presented the legislative, scientific, and public health dilemmas that accompany recommending criteria to control the exposure of workers to radon progeny in underground mines.

The development of this criteria document is subject to the provisions of two legislative mandates. First, the Occupational Safety and Health Act of 1970 [Public Law (PL) 91-596, which established NIOSH] requires safe and healthful working conditions for every working person. The Act further requires NIOSH to preserve our human resources by providing medical and other criteria that will ensure, insofar as practicable, that no worker will suffer diminished health, functional capacity, or life expectancy as a result of work experience [PL 91-596, Sections 6(b)(5)]. The Act also authorizes NIOSH to recommend new criteria to further improve working conditions [PL 91-596, Sections 22(c) and (d)]. In addition, the Federal Coal Mine Health and Safety Act of 1969 [PL 91-173] and the Federal Mine Safety and Health Amendments Act of 1977 [PL 95-164] require NIOSH to develop and revise recommended occupational safety and health standards for mine workers. Specifically, the Secretary of Health, Education, and Welfare (now the Secretary of Health and Human Services) is required to consider, "in addition to the attainment of the highest degree of health protection for the miner . . . the latest available scientific data in the field, the technical feasibility of the standards, and experience gained under this and other health statutes" [PL 91-173, Title 1, Section 101(d)]. These mandates have required NIOSH to weigh its obligation to assure the highest degree of health protection for miners against the technical feasibility of the recommended standard in the development of recommendations for controlling radon progeny exposure in underground mines.

The control of exposure to radon progeny presents an unprecedented problem because of the ubiquitous yet variable nature of their presence in mines and the ambient environment. To complicate this matter further, recent reports indicate that an exposure-related health risk may exist at background exposure levels.

The full ramifications of this dilemma can easily be appreciated by considering two points. The first is that dilution ventilation (the primary engineering approach to reducing the concentration of radon progeny in mines) is accomplished by the exchange of mine air with air from the outside environment. Obviously, this approach is not a viable option for the total elimination of radon progeny in underground mines because the outside air is also contaminated with radon progeny. In addition, this approach would not be a prudent community environmental public health measure in some situations because it involves releasing an additional burden of radon progeny to the ambient environment and thereby contributing to the background level in the immediate area of the mine. Thus ventilation cannot be used to totally eliminate exposure to radon progeny in mines.

The second point to consider in this dilemma is that the variable nature of radon progeny exposure in the ambient environment precludes recommending an annual cumulative exposure limit that includes both occupational and ambient contributions. Because ambient exposure varies, such a recommendation would result in an occupational exposure limit and associated risk that would vary with the locale. This approach is obviously undesirable, for it would lead to a nightmare of confusion and complicated enforcement requirements and would probably result in unequal protection of miners.

Data from both human and animal studies clearly demonstrate a direct link between lung cancer and radon exposure. Specific epidemiological studies provide a basis for quantitatively estimating human risk at various exposure levels. Such analyses clearly show that a radon exposure of 4 WLM (4 working level months) per year over a 30-year working lifetime (the current Mine Safety and Health Administration [MSHA] standard) poses a significant and unacceptable risk of lung cancer. This risk must be substantially reduced.

In recommending an exposure limit for radon progeny, NIOSH considered not only the results of its own risk assessment and the technical feasibility of the recommended standard, but also the uncertainty of the data available on risk. Uncertainties are inherent in both the risk assessment methods and the scientific data on which the risk assessment is based. This fact must be understood and acknowledged. Some of the factors involved in these uncertainties include the choice of risk assessment method and model, the measurement methods used for data collection, and risk estimates derived from data that are heavily weighted with higher exposures.

The first of these factors in risk uncertainty involves the choice of a risk assessment method and/or model (such as the Cox proportional hazards model used in the NIOSH risk assessment study). NIOSH has attempted to develop a mathematical model that best describes the lung cancer risk in miners exposed to radon progeny. The use of a risk assessment model is merely a practical way to work with a very complex problem. There are modeling approaches other than the one chosen for this study. Each choice would result in a somewhat different description of the relationship between radon progeny exposure and lung cancer risk. NIOSH has attempted to compare the alternatives that are available and applicable. NIOSH scientists have considered the differences that might arise through a review of the available scientific literature and discussions with other scientists who have evaluated this exposure-related lung cancer risk.

Although alternative models might yield minimally different quantitative risk estimates, none of them would lead the Institute to a qualitatively different risk assessment (i.e., that exposures to radon progeny at the current standard are associated with excesses of lung cancer).

The second factor involved in risk uncertainty is the measurement method used for data collection. This study involves a follow-up period of more than 35 years, more than 3,000 miners, and thousands of measurements. The

older data are subject to greater uncertainty than the more recent data because of improvements in the entire measurement process over the course of the study.

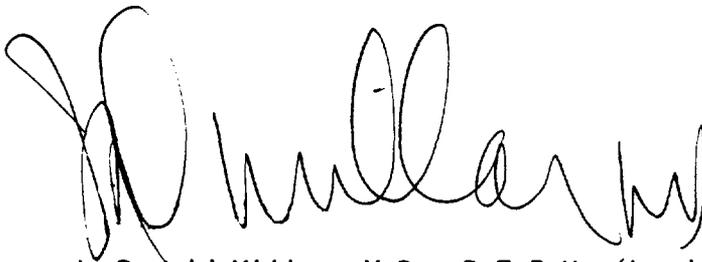
The third factor involved in risk uncertainty is the process of generating risk estimates at lower exposure levels. One consideration is that such risk estimates are derived from data heavily weighted by higher exposures (note that the annual cumulative exposures of most miners in this study are higher than either the current MSHA standard or the proposed NIOSH recommended exposure limit [REL]). Another consideration is the desirability of placing occupational risk in the context of background exposure risk. However, the latter has not been evaluated and would have to be estimated on the basis of occupational data. We therefore do not believe that it is currently possible to contrast these two types of risks. Nonetheless, EPA has generated some initial information on background exposure risk in A Citizen's Guide to Radon. This document indicates that action should be taken to lower radon progeny levels in homes with measured concentrations of 0.02 WL or greater. NIOSH estimates that this concentration would probably result in a cumulative exposure that is less than 1 WLM but within an order of magnitude of that value. New information is clearly needed on background exposure levels and the hazards associated with such exposure before occupational and nonoccupational risks can be reliably quantified and validly contrasted. Until these data are available, the final target exposure limits cannot be identified for control of this hazard in our total environment.

The uncertainties in the data and a recent study commissioned by the Bureau of Mines* on the feasibilities of controlling radon progeny levels in mines have been weighed along with the available evidence and the obligations of NIOSH. This process has resulted in an REL of 1 WLM per year. Our own quantitative risk assessment clearly shows that significant health risks are posed by an exposure level of 1 WLM per year over a 30-year working lifetime. NIOSH therefore regards this REL as an upper limit and further recommends that mine operators limit exposure to radon progeny to the lowest levels possible. In addition, NIOSH wishes to emphasize that this recommended standard contains many important provisions in addition to the annual exposure limit. These include recommendations for limited work shift concentrations of radon progeny, sampling and analytical methods, recordkeeping, medical surveillance, posting of hazardous information, respiratory protection, worker education and notification, and sanitation. All of these recommendations help minimize risk.

In summary, NIOSH has the legislative, scientific, and public health responsibility to protect the health of miners by developing recommendations

*Bloomster CH, Enderlin WI, Young JK, Dirks JA (1984). Cost survey for radon daughter control by ventilation and other control techniques. Volume 1. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152932.

that eliminate or minimize occupational risks. Although I am approving the recommended exposure limit of 1 WLM per year, I do not feel that this part of the recommended standard fully satisfies the Institute's commitment to protect the health of all of the Nation's miners. Future research may provide evidence of new and more effective methods for reducing occupational exposures to radon progeny, more reliable risk estimates at low exposure levels, and improved risk assessment methods. If new information demonstrates that a lower exposure limit constitutes both prudent public health and a feasible engineering policy, NIOSH will revise its recommended standard.

A handwritten signature in black ink, appearing to read 'J. Donald Millar', written in a cursive style.

J. Donald Millar, M.D., D.T.P.H. (Lond.)
Assistant Surgeon General
Director, National Institute for
Occupational Safety and Health
Centers for Disease Control

CONTENTS

| | |
|---|------|
| Foreword | iii |
| Acknowledgments | viii |
| I. Recommendations for a Radon Progeny Standard | 1 |
| Section 1. Definitions | 1 |
| Section 2. Environment (Workplace Air) | 2 |
| Section 3. Monitoring and Recording Exposures | 2 |
| Section 4. Medical Surveillance | 4 |
| Section 5. Posting | 6 |
| Section 6. Work Practices and Engineering Controls | 6 |
| Section 7. Respirator Selection and Credit for Respirator Use | 8 |
| Section 8. Informing Workers of the Hazards of Radon Progeny | 13 |
| Section 9. Sanitation | 13 |
| Section 10. Recordkeeping Requirements | 14 |
| II. Introduction | 16 |
| A. Scope | 16 |
| B. Current Standard | 16 |
| C. Uranium Decay Series | 17 |
| D. Units of Measure | 19 |
| E. Worker Exposure | 20 |
| F. Measurement Methods for Airborne Radon Progeny | 22 |
| G. Respirator Selection and Credit for Respirator Use | 28 |
| III. Basis for the Recommended Standard | 32 |
| A. Assessment of Effects | 32 |
| B. Risk Assessment | 39 |
| C. Technical Feasibility | 44 |
| D. Recommendations | 44 |
| IV. Research Needs | 47 |
| A. Epidemiologic Studies | 47 |
| B. Engineering Controls and Work Practices | 47 |
| C. Respiratory Protection | 47 |
| D. Environmental (Workplace) Monitoring | 48 |
| V. Public Health Perspective | 49 |
| References | 54 |
| Appendices | |
| I. Evaluation of Epidemiologic Studies Examining the Lung Cancer Mortality of Underground Miners | 65 |
| II. Quantitative Risk Assessment of Lung Cancer in U.S. Uranium Miners | 138 |
| III. Engineering Control Methods | 177 |
| IV. Grab Sampling Strategy Requirements for Determination of Radon Progeny Exposures | 193 |
| V. Medical Aspects of Wearing Respirators | 204 |

ACKNOWLEDGMENTS

The document was developed by the Division of Standards Development and Technology Transfer, National Institute for Occupational Safety and Health, Richard A. Lemen, Director, Richard W. Niemeier, Ph.D., Deputy Director, and William D. Wagner, Chief of the Document Development Branch. The criteria document manager was Mary Ballew. David D. Bayse, Ph.D., Robert Bernstein, M.D., Ph.D., Kenneth Busch, Burt Cooper, Kent Hatfield, Ph.D., Richard Hornung, Ph.D., Howard Ludwig, Lawrence Mazzuckelli, Theodore Meinhardt, Ph.D., Mary Newman, Ph.D., Sheldon Rabinovitz, Ph.D., Laurence Reed, Randall Smith, Sandra Susten, Ph.D., and Ralph Zumwalde are gratefully acknowledged for their contributions to the writing and critical review of this document. John Bainbridge, Nancy J. Bollinger, Donald L. Campbell, David Groth, M.D., Bryan Hardin, Ph.D., and John Whalen are also gratefully acknowledged for their contributions to the critical review of this document. Special appreciation is extended to Vanessa Becks, Carolyn Browning, Ruth Grubbs, Anne Hamilton, and Eileen Kuempel for their editorial review, to Richard Carlson and Ann Stirnkorb for their preparation of figures, and to Judy Curless, Brenda Ellis, Denise Hill, Susan Marksberry, and Carol A. Ritchey for their support in typing and preparing the document for publication.

I. RECOMMENDATIONS FOR A RADON PROGENY STANDARD

The National Institute for Occupational Safety and Health (NIOSH) recommends that worker exposure to radon progeny in underground mines be controlled by compliance with this recommended standard, which is designed to protect the health of underground miners over a working lifetime of 30 years. Mine operators should regard the recommended exposure limit for radon progeny as the upper boundary for exposure; they should make every effort to limit radon progeny to the lowest possible concentrations. This recommended standard will be reviewed and revised as necessary.

Radon progeny (also known as radon daughters) are the short-lived decay products of radon, an inert gas that is one of the natural decay products of uranium. The short-lived radon progeny (i.e., polonium-210, lead-214, bismuth-214, and polonium-214) are solids and exist in air as free ions or as ions attached to dust particles. The NIOSH recommended exposure limit (REL) is based on (1) evidence that a substantial risk of lung cancer is associated with an occupational exposure to radon progeny, and (2) the technical feasibility of reducing exposures. In this document, NIOSH presents recommendations that will protect miners employed year-round at any mine work area for as long as 30 years (the period of time used by MSHA as a miner's working lifetime). The exposure limit contained in this recommended standard is measurable by techniques that are valid, reproducible, and available to industry and government agencies. NIOSH has concluded that current technology is sufficient to achieve compliance with the recommended standard.

Because knowledge of the carcinogenic process is incomplete and no data exist to demonstrate a safe level of exposure to carcinogens, NIOSH maintains that occupational exposure to carcinogens such as radon progeny should be reduced to the lowest level technically achievable. Compliance with this standard does not relieve mine operators from complying with other applicable standards.

Section 1 - Definitions

(a) Miner

Miners include all mine personnel who are involved with any underground operation (e.g., drilling, blasting, haulage, and maintenance).

(b) Working Level

One working level (WL) is any combination of short-lived radon progeny in 1 liter (L) of air that will ultimately release 1.3×10^5 million electron volts (MeV) of alpha energy during decay to lead-210.

(c) Working Level Month

A working level month (WLM) is the product of the radon progeny concentration in WL and the exposure duration in months. For example, if a miner is exposed at a concentration of 0.083 WL for 1 month

(170 hours [hr]),* then the cumulative exposure for the month is 0.083 WLM. If the cumulative exposure of the same miner is 0.083 WLM for each of 12 consecutive months (2,040 hr), then the cumulative exposure for the year is 1 WLM.

(d) Work Area

A work area is any stope, drift heading, travelway, haulageway, shop, station, lunchroom, or any other underground location where miners work, travel, or congregate.

(e) Average Work Shift Concentration

The average work shift concentration is the average concentration of radon progeny present during a work shift in a given area. This concentration is used to represent the miner's breathing zone exposure to radon progeny.

Section 2 – Environment (Workplace Air)

(a) Recommended Exposure Limit (REL)

Exposure to radon progeny in underground mines shall not exceed 1 WLM per year, and the average work shift concentration shall not exceed 1/12 of 1 WL (or 0.083 WL). The REL of 1 WLM per year is an upper limit of cumulative exposure, and every effort shall be made to reduce exposures to the lowest levels possible.

(b) Sampling and Analysis

Grab samples for radon progeny in the workplace shall be taken and analyzed using working level monitors, the Kusnetz method, or any other method at least equivalent in accuracy, precision, and sensitivity. Sampling and analytical methods are described in Chapter II. Details of the recommended sampling strategy are contained in Appendix IV. The recommended sampling strategy allows the use of grab samples for estimating the average work shift concentration of radon progeny.

Section 3 – Monitoring and Recording Exposures

(a) Exposure Monitoring

All operators of underground mines shall perform environmental evaluations in all work areas to determine exposures to radon progeny.

(1) An initial environmental evaluation shall be conducted in each work area to determine the average work shift concentration of radon progeny.

*Note that Mine Safety and Health Administration (MSHA) regulations are based on 173 hr per month.

(2) Periodic environmental evaluations shall be conducted at intervals (as described in Appendix IV) in each work area. An alternative sampling strategy may be used if the mine operator can demonstrate that it effectively monitors exposure to radon progeny.

(3) If environmental monitoring in a work area indicates that the average work shift concentration of radon progeny exceeds 1/12 WL (as described in Appendix IV), the mine operator shall prepare an action plan describing the types of engineering controls and work practices that will be implemented to reduce the average work shift concentration in that area.

(b) Exposure Monitoring Records

The mine operator shall determine and record the exposure to radon progeny. Each miner's exposure shall be calculated using monitoring data obtained for the areas in which the miner worked. These records shall include (1) locations, dates, and times of measurements, (2) sampling and analytical methods used, (3) the number, duration, and results of the samples taken, and (4) all items required by Sections 3(b)(2) and (3). All records shall be retained at the mine site or nearest mine office as described in Section 10.

(1) Calculating the Miner's Daily Exposure

The average work shift concentration of radon progeny for each work area shall be used to calculate each miner's daily exposure. If no monitoring has been conducted in a work area on a particular day, the daily average work shift concentration for that area shall be determined by averaging the results obtained on the last day of monitoring with the results from the next day that monitoring is conducted.

A miner's exposure (in WLM) for a given area is calculated as follows:

$$WLM = \frac{WL \times T}{170 \text{ hr}}$$

where WL is the average work shift concentration of radon progeny, T is the total time (hours) spent in the area, and 170 is the number of hours worked per month.

A miner's total cumulative exposure for the year is the sum of the daily exposures (as calculated above) for all work areas in which time was spent during the work shift.

(2) Uranium Mines

Exposure to radon progeny shall be recorded daily for each uranium miner. These records shall include the miner's name, social security number, the time spent in each work area, estimated exposure to radon progeny for each work area as determined in

Section 3(b)(3), and (if applicable) the type of respiratory protection and duration of its use.

(3) Nonuranium Mines

Exposure to radon progeny shall be recorded daily for all miners assigned to work in areas where environmental monitoring for radon progeny is required as described in Appendix IV. These exposure monitoring records shall include the miner's name, social security number, time the miner has spent in each work area, estimated exposure to radon progeny for each work area as determined in Section 3(b)(3), and (if applicable) the type of respiratory protection used and the duration of its use.

(4) Respirator Credit

The type of respirator worn and the credit given for wearing it (see Section 7) shall be recorded for each miner. Mine operators shall record both the average work shift concentration of radon progeny and the adjusted exposure concentration calculated by using the respirator credit. The adjusted exposure concentration shall be used to determine the miner's cumulative exposure for compliance with the REL of 1.0 WLM/year.

Section 4 - Medical Surveillance

(a) General

(1) The mine operator shall institute a medical surveillance program for all miners.

(2) The mine operator shall ensure that all medical examinations and procedures are performed by or under the direction of a licensed physician.

(3) The mine operator shall provide the required medical surveillance at a reasonable time and place without loss of pay or cost to the miners.

(4) The mine operator shall provide the following information to the physician performing or responsible for the medical surveillance program: a copy of the radon progeny standard, the miner's duration of employment, the miner's cumulative exposure to radon progeny (or an estimate of potential exposure to radon progeny if the miner is a new employee), a description of the miner's duties as they relate to his exposure, and a description of any protective equipment the miner has used or may be required to use.

(5) The mine operator or physician shall counsel tobacco-smoking miners about their increased risk of developing lung cancer from the combined exposure to tobacco smoke and radon progeny. The mine operator or physician shall encourage the miner to participate in a

smoking cessation program. The mine operator shall enforce a policy prohibiting smoking at the mine site.

(6) The physician shall provide the mine operator and the miner with a written statement describing any medical conditions found during the preplacement or periodic medical examinations that may increase the miner's health risk when exposed to radon progeny. This written statement shall not reveal specific findings, but shall include any recommended limitations on the miner's exposure to radon progeny or ability to use respirators and other personal protective equipment.

(b) Preplacement Medical Examination

The preplacement medical examination of each miner shall include the following:

(1) A comprehensive medical and work history (including smoking history) that emphasizes the identification of existing medical conditions and attempts to elicit information about previous occupational exposure to radon progeny.

(2) A thorough examination of the miner's respiratory system, including pulmonary function tests. The initial and subsequent pulmonary function tests shall include determination of forced vital capacity (FVC) and forced expiratory volume in 1 second (FEV₁) using the current American Thoracic Society (ATS) recommendations on instrumentation, technician training, and interpretation. A prospective miner with symptomatic, spirometric, or radiographic evidence of pulmonary impairment should be counseled about the risks of continued exposure.

(3) A postero-anterior chest X-ray using the current ATS recommendations on instrumentation, technician training, and interpretation.

(4) Other tests deemed appropriate by the physician.

(c) Periodic Medical Examination

The periodic medical examination for each miner shall include the following:

(1) An annual update of medical and work histories (including smoking history).

(2) An evaluation of the miner's respiratory system. Because of the potential for chronic respiratory disease, this evaluation shall include spirometry at intervals determined by the physician. Miners that have spirometric or radiographic evidence or symptoms of pulmonary impairment should be counseled by the physician regarding the risks of continued exposure.

(3) A postero-anterior chest X-ray at intervals determined by the physician using the current ATS recommendations on instrumentation, technician training, and interpretation. Periodic chest X-rays are recommended for monitoring miners exposed to fibrogenic respiratory hazards (e.g., quartz). Ordinarily, chest X-rays may be obtained every 5 years for the first 15 years of employment and every 2 years thereafter, depending on the nature and intensity of exposures and their related health risks. A recent X-ray obtained for other purposes (e.g., upon hospitalization) may be substituted for the periodic X-ray if it is of acceptable quality.

(4) Other tests deemed appropriate by the physician.

Section 5 - Posting

All warning signs shall be printed in both English and the predominant language of non-English-reading miners. Miners unable to read the posted signs shall be informed verbally about the hazardous areas of the mine and the instructions printed on the signs.

(a) Readily visible signs containing the following information shall be posted at mine entrances or in work areas that require environmental monitoring for radon progeny as described in Appendix IV:

**AUTHORIZED PERSONNEL ONLY
DANGER!
POTENTIAL RADIATION HAZARD
RADON PROGENY**

(b) If respiratory protection is required, the following statement shall be added in large letters to the sign required in Section 5(a):

RESPIRATORY PROTECTION REQUIRED IN THIS AREA

Section 6 - Work Practices and Engineering Controls

Effective work practices and engineering controls shall be instituted by the mine operator to reduce the concentration of radon progeny to the lowest technically achievable limit. Since there is no typical mine and each operation has some unique features, the work practices and engineering controls in this section may need to be adapted for use in particular situations.

(a) **Work Practices**

(1) **Ore Extraction and Handling**

Examples of effective ore extraction and handling procedures include the following: minimizing the number of ore faces simultaneously exposed, performing retreat mining toward intake air, limiting the underground storage and handling of ore, locating ore transfer points away from ventilation intakes, removing dust

spilled from ore cars, minimizing ore spillage by maintaining roadways and carefully loading haulage vehicles, and covering ore until it is moved to the surface.

(2) Blasting

Blasting should be performed at the end of the work shift whenever possible. Miners shall be evacuated from exhaust drifts until environmental sampling confirms that the average work shift concentration of radon progeny does not exceed 1/12 WL. Refer to Section 7 if respiratory protection is required for subsequent reentry.

(3) Worker Rotation

The mine operator shall not use the planned rotation of miners to maintain an individual's exposure below the REL of 1.0 WLM per year. NIOSH acknowledges, however, that some miners may inadvertently be exposed to short-term high concentrations of radon progeny. For example, such exposures may occur when engineering controls fail. To ensure that the miners' cumulative exposure remains below the REL in such circumstances, it may be necessary to transfer them to other jobs or work areas that have lower concentrations of radon progeny. Miners transferred under these circumstances shall retain their pay as prescribed for coal miners under Section 203(b) of the Federal Coal Mine Safety and Health Act of 1977.

(b) Engineering Controls

Mechanical exhaust ventilation used alone or in combination with other engineering controls and work practices can effectively reduce exposures to radon progeny. Ventilation systems discharging outside the mine shall conform with applicable local, State, and Federal [40 CFR*61, Subpart B] air pollution regulations and shall not constitute a hazard to miners or to the general population.

(1) Ductwork shall be kept in good repair to maintain designed airflows. The effectiveness of mechanical ventilation systems shall be determined periodically and as soon as possible after any significant changes have been made in production or control. A log shall be kept showing designed airflow and the results of all airflow measurements.

(2) Fans shall be operated continuously in the work areas of an active mine and before the opening of a previously inactive mine or inactive section until environmental sampling confirms that the average work shift concentrations of radon progeny do not exceed 1/12 WL. Refer to Section 7 if respiratory protection is required.

*Code of Federal Regulations. See CFR in references.

(3) Fresh air shall be provided to miners in dead end areas near the working faces.

(4) Bulkheads, backfill, and sealants shall be used to control exposures as appropriate.

Appendix III provides a general discussion of engineering control methods.

Section 7 - Respirator Selection and Credit for Respirator Use

(a) General Considerations

NIOSH has determined that a radon progeny exposure limit of 1.0 WLM per year is technically achievable in mines through the use of effective work practices and engineering controls. Over a 30-year working lifetime, this exposure limit will reduce but not eliminate the risk of lung cancer associated with exposure to radon progeny. NIOSH considers respirators to be one of the last options for worker protection. Work practices and engineering controls are more effective means for limiting exposures and providing a safe environment for all workers. Respirator use in underground mines is not always practical for a number of reasons, including the additional physiological burden and safety hazards they pose. NIOSH therefore recommends that engineering controls and work practices be used where technically achievable to control the exposure of miners to radon progeny.

Compliance with an exposure limit of 1.0 WLM per year requires an average exposure of 1/12 WL throughout the year to ensure that the miner can work for an entire year (i.e., 2,040 hr). For average work shift concentrations above 1/12 WL, NIOSH recommends mandatory respirator use as well as the implementation of engineering controls and work practices to reduce exposure to radon progeny.

Occupational exposure to radon progeny above background concentrations has been associated with excess lung cancer risk. Therefore, regardless of the exposure concentration, NIOSH advises the use of respirators to further reduce exposure and decrease the risk of lung cancer.

Respiratory protection shall be used by miners (1) when work practices and engineering controls are not adequate to limit average work shift concentrations of radon progeny to 1/12 WL, (2) when entering a mine area where concentrations of radon progeny are unknown, or (3) during emergencies. Use only those respirators approved by NIOSH or the Mine Safety and Health Administration (MSHA).

(b) Respirator Protection Program

Whenever respirators are used, a complete respiratory protection program shall be instituted. This program must follow the recommendations contained in ANSI Z88.2-1969 (published by the American National Standards Institute) and the respirator-use criteria in 30 CFR 57.5005.

The respiratory protection program described in ANSI Z88.2-1969 requires the following:

- (1) A written program for respiratory protection that contains standard operating procedures governing the selection and use of respirators.
- (2) Periodic worker training in the proper use and limitations of respirators.
- (3) Evaluation of working conditions in the mine.
- (4) An estimate of anticipated exposure.
- (5) An estimate of the physical stress that will be placed on the miner. A detailed medical examination of each miner shall be conducted according to the guidelines set forth in Appendix V.
- (6) Routine inspection, maintenance, disinfection, proper storage, and evaluation of respirators.
- (7) Information concerning the manufacturers' instructions for respirator fit-testing and proper use.

(c) Respirator Selection

NIOSH makes the following recommendations for respirator selection:

- (1) A respirator is not required for exposure to average work shift concentrations less than or equal to 1/12 WL.
- (2) For exposure to average work shift concentrations greater than 1/12 WL, NIOSH recommends those respirators listed in Table I-1.
- (3) For entry into areas where radon progeny concentrations are unknown or exceed 166 WL, or for emergency entry, NIOSH recommends only the most protective respirators (any full-facepiece, positive-pressure, self-contained breathing apparatus [SCBA] or full-facepiece, positive-pressure, supplied-air respirator and SCBA combination).

These recommendations are based on the fact that radon progeny exist as particulates and that miners are not exposed to hazardous concentrations of nonparticulate contaminants. If protection against nonparticulate contaminants is required, different types of respirators must be selected.

(d) Credit for Respirator Use

When respirators are worn properly, the miner's average work shift exposure can be reduced by a factor that depends on the class of respirator worn. Table I-1 provides the credit factors for the various classes of respirators. For example, if a miner wears a helmet-type,

Table I-1.--Respirator recommendations for radon progeny

| Average work shift concentration of radon progeny (WL) | Respirator recommendations | Credit factor for respirator use | |
|---|--|-------------------------------------|-----------------|
| | | 65% utilization | 90% utilization |
| 0 to 0.083 (1/12) | No respirator required | NA [†] | NA |
| >0.083 to ≤ 0.42 | Any disposable respirator equipped with a HEPA [§] filter | 2.1 | 3.6 |
| | Any more protective respirator | # | # |
| >0.42 to ≤ 0.83 | Any air-purifying half-mask respirator equipped with a HEPA filter | 2.4 | 5.3 |
| | Any SAR ^{**} equipped with a half- mask and operated in a demand (negative-pressure) mode | 2.4 | 5.3 |
| | Any more protective respirator | # | # |
| >0.83 to ≤ 2.08 | Any powered PAPR ^{††} equipped with a hood or helmet and a HEPA filter | 2.7 | 7.4 |
| | Any SAR equipped with a hood or helmet and operated in a continuous flow mode | 2.7 | 7.4 |
| | Any more protective respirator | # | # |

See footnotes at end of table.

Table I-1 (Continued).—Respirator recommendations for radon progeny

| Average work shift concentration of radon progeny | Respirator recommendations | Credit factor for respirator use | |
|---|--|-------------------------------------|-----------------|
| | | 65% utilization | 90% utilization |
| >2.08 to ≤ 4.15 | Any air-purifying, full face- piece respirator equipped with a HEPA filter | 2.8 | 8.5 |
| | Any PAPR equipped with a tight- fitting facepiece and a HEPA filter | 2.8 | 8.5 |
| | Any SAR equipped with a full facepiece and operated in a demand (negative-pressure) mode | 2.8 | 8.5 |
| | Any SAR equipped with a tight- fitting facepiece and operated in a continuous-flow mode | 2.8 | 8.5 |
| | Any self-contained breathing apparatus (SCBA) equipped with a full facepiece and operated in a demand (negative-pressure) mode | 2.8 | 8.5 |
| | Any more protective respirator | # | # |
| >4.15 to ≤ 83.0 | Any SAR equipped with a half- mask and operated in a pressure- demand or other positive-pressure mode | 2.9 | 9.9 |
| | Any more protective respirator | # | # |

See footnotes at end of table.

Table I-1 (Continued).--Respirator recommendations for radon progeny

| Average work shift concentration of radon progeny* | Respirator recommendations | Credit factor for respirator use | |
|--|--|----------------------------------|-----------------|
| | | 65% utilization | 90% utilization |
| >83.0 to ≤ 166.0 | Any SAR equipped with a full facepiece and operated in a pressure demand or other positive pressure mode | 2.9 | 10.0 |
| | Any more protective respirator | # | # |
| >166.0 or unknown concentration or emergency entry | Any SCBA equipped with a full facepiece and operated in a pressure demand or other positive pressure mode | 2.9 | 10.0 |
| | Any SAR equipped with a full facepiece operated in a pressure demand or other positive pressure mode in combination with an auxiliary self-contained breathing apparatus operated in a pressure demand or other positive pressure mode | 2.9 | 10.0 |
| Emergency escape | Any self-contained self-rescuer (SCSR) | NA | NA |

*As estimated using the sampling techniques described in Appendix IV.

†NA=Not applicable.

§HEPA = high-efficiency particulate air.

#See appropriated credit factors below.

**SAR = supplied-air respirator.

††PAPR = powered air-purifying respirator.

powered, air-purifying respirator (PAPR) for 65% of the work shift and the radon progeny concentration in the work area is 0.3 WL, then the miner's exposure can be adjusted by dividing 0.3 WL by 2.7, the credit factor for this class of respirator. This results in an adjusted exposure of 0.11 WL for that miner. Respirator credit is discussed in detail in Chapter 11.

Section 8 - Informing Workers of the Hazards of Radon Progeny

(a) Notification of Hazards

The mine operator shall provide all miners with information about workplace hazards before job assignment and at least annually thereafter.

(b) Training

(1) The mine operator shall institute a continuing education program conducted by persons with expertise in occupational safety and health. The purpose of this program is to ensure that all miners have current knowledge of workplace hazards, effective work practices, engineering controls, and the proper use of respirators and other personal protective equipment. This program shall also include a description of the general nature of the environmental and medical surveillance programs and the advantages of participating in them. This information shall be kept on file and be readily available to miners for examination and copying. The mine operator shall maintain a written plan of these training and surveillance programs.

(2) Miners shall be instructed about their responsibilities for following proper work practices and sanitation procedures necessary to protect their health and safety.

Section 9 - Sanitation

(a) Eating and Drinking

The preparation, storage, dispensing (including vending machines), or consumption of food shall be prohibited in any area where a toxic material is present. The mine operator shall provide facilities so that miners can wash their hands and faces thoroughly with soap or mild detergent and water before eating or drinking.

(b) Smoking

Smoking shall be prohibited in underground work areas.

(c) Toilet Facilities

The mine operator shall provide an adequate number of toilet facilities and encourage the miners to wash their hands thoroughly with soap or mild detergent and water before and after using these facilities.

(d) Change Rooms

(1) The mine operator shall provide clean change rooms for the miners.

(2) The mine operator shall provide storage facilities such as lockers to permit the miners to store street clothing and personal items.

(e) Showers

The mine operator shall provide showers and encourage the miners to shower at the end of the work shift.

(f) Laundering

(1) The mine operator shall provide for the cleaning, laundering, or disposal of contaminated work clothing and equipment.

(2) The mine operator shall ensure that contaminated work clothing or equipment that is to be cleaned, laundered, or disposed of is placed in a closed container to prevent dispersion of dust.

(3) Any person who cleans or launders this contaminated work clothing or equipment must be informed by the operator that it may be contaminated with radioactive materials.

Section 10 - Recordkeeping Requirements

(a) Record Retention

(1) The mine operator shall retain all records of the monitoring required in Section 3(b).

(2) All monitoring records shall be retained for at least 40 years after termination of employment.

(3) The mine operator shall retain the medical records required by Section 4. These records shall be retained for at least 40 years after termination of employment.

(b) Availability of Records

The miner shall have access to his medical records and be permitted to obtain copies of them. Records shall also be made available to former miners, or their representative and to the designated representatives of the Secretary of Labor and the Secretary of Health and Human Services.

(c) Transfer of Records

(1) Upon termination of employment, the mine operator shall provide the miner with a copy of his records specified in Section 10(a).

- (2) Whenever the mine operator transfers ownership of the mine, all records described in this section shall be transferred to the new operator, who shall maintain them as required by this standard.
- (3) Whenever a mine operator ceases to do business and there is no successor, the mine operator shall notify the miners of their rights of access to those records at least 3 months before cessation of business.
- (4) The Director of NIOSH shall be notified in writing before (a) a mine operator ceases to do business and there is no successor to maintain records, and (b) the mine operator intends to dispose of those records.
- (5) No records shall be destroyed until the Director of NIOSH responds in writing to the mine operator.

II. INTRODUCTION

A. Scope

Radon is a gas that diffuses continuously from surrounding rock and broken ore into the air of underground mines, where it may accumulate; radon may also be carried into mines through groundwater containing dissolved radon [Snihs 1981]. Radon gas may be inhaled and immediately exhaled without appreciably affecting the respiratory tissues. However, when attached or unattached radon progeny are inhaled, they may be deposited on the epithelial tissues of the tracheobronchial airways. Alpha radiation may subsequently be emitted into those tissues from polonium-218 and polonium-214, thus posing a cancer risk to miners who inhale radon progeny.

This document presents the criteria and recommendations for an exposure standard that is intended to decrease the risk of lung cancer in miners occupationally exposed to short-lived, alpha-emitting decay products of radon (radon progeny) in underground mines. The REL for radon progeny applies only to the workplace and is not designed to protect the population at large. The REL is intended to (1) protect miners from the development of lung cancer, (2) be measurable by techniques that are valid, reproducible, and available to industry and government agencies, and (3) be technically achievable.

B. Current Standard

MSHA has established radiation protection standards for workers in underground metal and nonmetal mines [30 CFR 57.5037 through 57.5047]. This standard limits a miner's radon progeny exposure to a concentration of 1.0 WL and an annual cumulative exposure of 4 WLM. Each WLM is determined as a 173-hr cumulative, time-weighted exposure [30 CFR 57.5040(6)]. Smoking is prohibited in all areas of a mine where radon progeny exposures must be determined; respiratory protection is required in areas where the concentration of radon progeny exceeds 1.0 WL.

According to current MSHA regulations, the exhaust air of underground mines must be sampled to determine the concentration of radon progeny.

1. Uranium Mines

If the concentration of radon progeny in the exhaust air of a uranium mine exceeds 0.1 WL, samples representative of a miner's breathing zone must be taken at random times every 2 weeks in each work area (i.e., stopes, drift headings, travelways, haulageways, shops, stations, lunchrooms, or any other place where miners work, travel, or congregate). If concentrations of radon progeny exceed 0.3 WL in a work area, sampling must be done weekly until the concentration has been reduced to 0.3 WL or less for 5 consecutive weeks.

Uranium mine operators must calculate, record, and report to MSHA the radon progeny exposure of each underground miner. The records must

include the miner's time in each work area and the radon progeny concentration measured in each of those areas.

2. Nonuranium Mines

If the concentration of radon progeny in the exhaust air of nonuranium mines exceeds 0.1 WL, and if concentrations are between 0.1 and 0.3 WL in an active working area, samples representative of a worker's breathing zone must be taken at least every 3 months at random times until the concentrations of radon progeny are less than 0.1 WL in that area. Samples must be taken annually thereafter. If the concentration of radon progeny exceeds 0.3 WL in a working area, samples must be taken at least weekly until the concentration has been reduced to 0.3 WL or less for 5 consecutive weeks. Operators of nonuranium mines must calculate, record, and report to MSHA the radon progeny exposures of miners assigned to areas with concentrations of radon progeny exceeding 0.3 WL. The records must include the miner's time in each work area and the radon progeny concentration measured in each of those areas.

C. Uranium Decay Series

Figure 11-1 shows the sequence by which the most abundant isotope of uranium (^{238}U) decays to a radioactively stable isotope of lead (^{206}Pb). Radon (^{222}Rn) is an inert gas with a radiologic half-life of 3.8 days; it is a product of the natural decay of radium (^{226}Ra). When radon decays, alpha particles and gamma radiation are emitted, and an isotope of polonium (^{218}Po) is formed. Polonium-218 (^{218}Po) and its decay products--lead-214 (^{214}Pb), bismuth-214 (^{214}Bi), and polonium-214 (^{214}Po)--are commonly referred to as short-lived radon progeny because they have half-lives of 27 minutes or less (see Figure 11-1). Both polonium-218 and polonium-214 emit alpha particles as they decay. The short-lived progeny are solids and exist in air as free ions (unattached progeny) or as ions adsorbed to dust particles (attached progeny).

Because it is a gas, radon diffuses through rock or soil and into the air of underground mines, where it may accumulate; radon may also be carried into mines through groundwater containing dissolved radon [Snihs 1981]. Radon may be inhaled and immediately exhaled without appreciably affecting the respiratory tissues. However, when the radon progeny (either attached or unattached) are inhaled, they may be deposited in the epithelial tissues of the tracheobronchial airways, where alpha radiation from polonium-218 and polonium-214 may be subsequently emitted. The quantity of mucus in those airways and the efficiency of its clearance (retrograde ciliary action) into the esophagus are important factors that affect the total radiation absorbed at a specific site within the respiratory tract.

Alpha particles are energetic helium nuclei. As they pass through tissue, they dissipate energy by the excitation and ionization of atoms in the tissue; it is this process that damages cells. Because alpha particles travel less than 100 micrometers in tissue, intense ionization occurs close to the site of deposition of the inhaled alpha-emitting radon progeny. Beta particles (electrons) and gamma radiation (shortwave electromagnetic radiation) can also cause ionization in tissues, but they travel farther

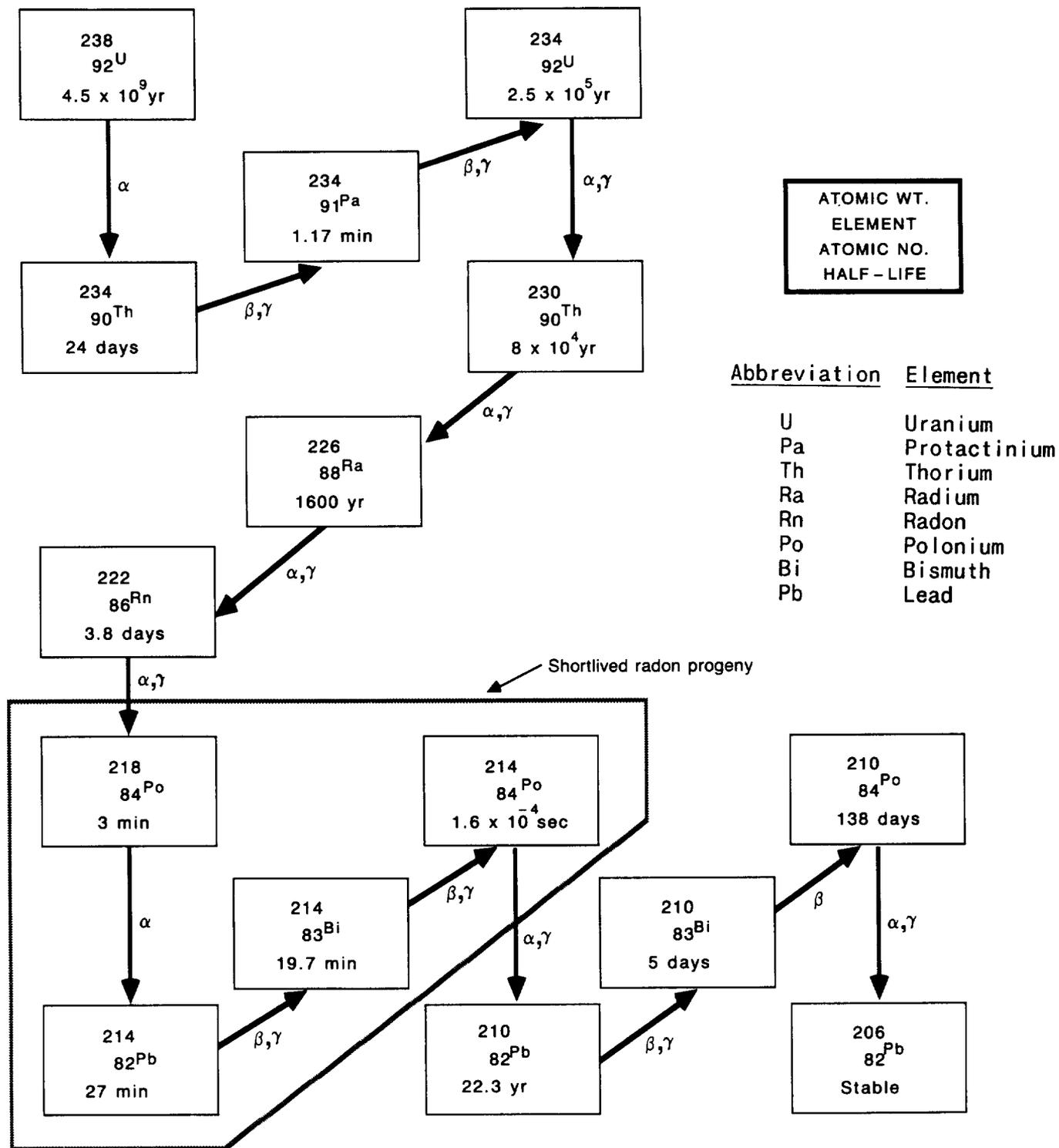


Figure 11-1.--The uranium (^{238}U) decay series.
 (Taken from Radiation Policy Council 1980.)

through tissues and dissipate less energy per unit path length than do alpha particles [Casarett 1968; Wang et al. 1975; Shapiro 1981]. The beta particles and gamma radiation emitted by radon progeny make a negligible contribution to the radiation dose in the lung [Evans 1969].

D. Units of Measure

The common unit of radioactivity is the curie (Ci), which is the rate at which the atoms of a radioactive substance decay; 1 Ci equals 3.7×10^{10} disintegrations per second (dps). The picocurie (pCi) corresponds to 3.7×10^{-2} dps. The International System of Units (SI) unit of radioactivity is the becquerel (Bq), which is equivalent to 1 dps. Therefore, 1 pCi is equivalent to 0.037 Bq.

When radon gas and radon progeny are inhaled, the radiation exposure is primarily caused by the short-lived radon progeny (polonium-218, lead-214, bismuth-214, and polonium-214, which are deposited in the lung) rather than by the radon gas. Because it was not feasible to routinely measure the individual radon progeny, the U.S. Public Health Service introduced the concept of the working level, or WL [Holaday et al. 1957]. The WL unit represents the amount of alpha radiation emitted from the short-lived radon progeny. One WL is any combination of short-lived radon progeny in 1 liter (L) of air that will ultimately release 1.3×10^5 million electron volts (MeV) of alpha energy during decay to lead-210. The SI unit of measure for potential alpha energy concentration is joules per cubic meter of air (J/m^3); 1 WL is equal to $2.08 \times 10^{-5} \text{ J}/\text{m}^3$ [ICRP 1981].

The equilibrium between radon gas and radon progeny must be known in order to convert units of radioactivity (Ci or Bq) to a potential alpha energy concentration (WL or J/m^3). The equilibrium factor (F) is defined as the ratio of the equilibrium-equivalent concentration of the short-lived radon progeny to the actual concentration of radon in air [ICRP 1981]. When the equilibrium factor approaches 1.0, it means that the concentration of radon progeny is increasing relative to the concentration of radon. At complete radioactive equilibrium (F=1.0), the rate of radon progeny decay equals the rate at which the progeny are produced. Thus the radioactivity of the decay products equals the radioactivity of the radon [Shapiro 1981]. In underground mines, the equilibrium factor mainly depends on the ventilation rate and the aerosol concentration [Urban et al. 1985]. Values of F ranging from 0.08 to 0.65 are typical in underground mines [Breslin et al. 1969]. Radioactivity and potential alpha energy concentration values at various equilibria are presented in Table II-1.

The common unit of measure for human exposure to radon progeny is the working level month (WLM). One WLM is defined as the exposure of a worker to radon progeny at a concentration of 1.0 WL for a working period of 1 month (170 hr).^{*} The SI unit for WLM is joule-hour per cubic meter of air ($\text{J-h}/\text{m}^3$); 1 WLM is equal to $3.6 \times 10^{-3} \text{ J-h}/\text{m}^3$.

^{*}Note that MSHA regulations are based on 173 hr per month.

Table II-1.--Potential alpha energy concentration as a function of the equilibrium factor

| Equilibrium factor (F)* | Radioactivity | | Potential alpha energy concentration | |
|-------------------------|---------------|-------|--------------------------------------|-----------------------|
| | pCi | Bq | WL | J/m ³ |
| 0.30 | 1 | 0.037 | 0.003 | 6.24x10 ⁻⁸ |
| 0.30 | 333 | 12.3 | 1.000 | 2.08x10 ⁻⁵ |
| 0.50 | 1 | 0.037 | 0.005 | 1.04x10 ⁻⁷ |
| 0.50 | 200 | 7.40 | 1.000 | 2.08x10 ⁻⁵ |
| 1.00 | 1 | 0.037 | 0.010 | 2.08x10 ⁻⁷ |
| 1.00 | 100 | 3.70 | 1.000 | 2.08x10 ⁻⁵ |

*F is defined as the quotient of the equilibrium-equivalent radon progeny activity divided by the radon activity.

The rad (radiation absorbed dose) is the unit of measure for the absorbed dose of ionizing radiation. One rad corresponds to the energy transfer of 6.24×10^7 MeV per gram of any absorbing material [Shapiro 1981]. The rem (roentgen equivalent man) is the unit of measure for the dose equivalent of any ionizing radiation in man. One rem is equivalent to one rad multiplied by a radiation quality factor (QF). The radiation QF expresses the relative effectiveness of radiation with differing linear-energy-transfer (LET) values to produce a given biological effect. The radiation QFs for beta particles and gamma radiation are each approximately 1; the radiation QF for alpha radiation varies from 10 to 20 [NCRP 1975; ICRP 1977; NCRP 1984a]. For equal doses of absorbed radiation (rads), the dose equivalent (rems) attributed to alpha particles is 10 to 20 times greater than the dose equivalent attributed to high-energy beta particles or gamma radiation. The SI unit of measure for the dose equivalent is the sievert (Sv). One rem is equal to 0.01 Sv [Shapiro 1981].

E. Worker Exposure

In 1986, 22,499 workers were employed in 427 metal and nonmetal mines in the United States. In the past few years, the number of underground uranium mines operating in the United States has decreased dramatically from 300 in 1980 [Federal Register 1986] to 16 in 1984 [MSHA 1986]. Accordingly, the number of miners employed in these mines has also decreased from 9,076 in 1979 [Cooper 1981], to 1,405 in 1984 [AIF 1984], and to 448 in 1986 [MSHA 1986].

Table II-2 shows the range in concentrations of airborne radon progeny measured in U.S. underground metal and nonmetal mines from 1976 through 1985 [MSHA 1986]. As illustrated in Table II-3, 38 of the 254 operating underground nonuranium mines sampled during fiscal year 1985 contained concentrations of airborne radon progeny equal to or greater than 0.1 WL in

Table 11-2.--Radon progeny concentrations (WL) in underground metal and nonmetal mines from 1976 through 1985*

| Type of mine | Range of annual geometric mean concentrations | Range of highest annual concentrations (95th percentile) |
|----------------------|---|--|
| Boron | 0.01-0.05 | 0.00-1.10 |
| Clay (common) | 0.01-0.21 | 0.01-0.54 |
| Clay (fire) | 0.04-0.20 | 0.22-0.83 |
| Copper Ore | 0.02-0.08 | 0.04-1.45 |
| Fluorspar | 0.01-0.29 | 0.03-2.80 |
| Gilsonite | 0.01-0.02 | 0.00-0.23 |
| Gold | 0.03-0.16 | 0.18-4.06 |
| Gypsum | 0.01-0.06 | 0.00-0.56 |
| Iron Ore | 0.01-0.28 | 0.02-0.73 |
| Lead/zinc | 0.01-0.13 | 0.08-1.03 |
| Lime | 0.01-0.09 | 0.01-0.34 |
| Limestone (crushed) | 0.01-0.04 | 0.03-0.70 |
| Marble (crushed) | 0.01-0.04 | 0.02-0.10 |
| Marble (dimension) | 0.01-0.02 | 0.00-0.09 |
| Metal† | 0.01-0.33 | 0.01-1.09 |
| Molybdenum | 0.02-0.08 | 0.09-0.96 |
| Oil sand | 0.01-0.02 | 0.00-0.04 |
| Oil shale | 0.01-0.01 | 0.00-0.08 |
| Perlite | 0.01-0.02 | 0.00-0.02 |
| Phosphate (rock) | 0.12-1.20 | 0.49-1.69 |
| Platinum | 0.01-0.13 | 0.00-0.22 |
| Potash | 0.01-0.02 | 0.00-0.09 |
| Potash, soda, borate | 0.01-0.02 | 0.00-0.03 |
| Salt (rock) | 0.01-0.06 | 0.03-0.10 |
| Sandstone (crushed) | 0.01-0.11 | 0.01-0.52 |
| Silver | 0.02-0.09 | 0.08-0.68 |
| Slate (dimension) | 0.02-0.25 | 0.11-3.00 |
| Talc (pyrophyllite) | 0.02-0.12 | 0.22-1.10 |
| Tungsten | 0.02-0.31 | 0.07-1.50 |
| Uranium | 0.11-0.36 | 0.80-2.73 |
| Uranium/vanadium | 0.10-0.25 | 0.76-4.80 |

*Adapted from Mine Safety and Health Administration data [MSHA 1986].

†Not elsewhere classified.

Table II-3.--Nonuranium mines with radon progeny concentrations above 0.1 WL (producing mines during fiscal year 1985*)†

| Mine product | Number of mines | Concentration (WL) |
|--|-----------------|--------------------|
| Clay, copper, gold, lead or zinc, molybdenum, silver, talc | 11 | 0.1 to <0.2 |
| Clay, copper, gold, lead or zinc, molybdenum, silver, talc | 8 | 0.2 to <0.3 |
| Clay, copper, gold, iron, lead or zinc, molybdenum, silver, tungsten | 12 | 0.3 to <1.0 |
| Gold, lead or zinc, metal (not elsewhere classified), phosphate, silver, slate | 7 | 1.0 and above |
| Total | 38 | --- |

*Samples for radon progeny were taken in 254 mines from October 1, 1984, through September 30, 1985.

†Adapted from Mine Safety and Health Administration data [MSHA 1986].

at least one work area; 19 of those mines had concentrations 0.3 WL or greater in at least one work area [MSHA 1986]. With an estimated average of 55 workers per mine, approximately 2,090 nonuranium miners were at risk of exposure to radon progeny concentrations equal to or greater than 0.1 WL in 1985 [MSHA 1986].

Table II-4 presents the annual cumulative radon progeny exposures of miners in 20 U.S. underground uranium mines in 1984; these data are presented by job category. Of the 1,405 underground uranium miners working in 1984, 400 (28%) had annual cumulative exposures to radon progeny greater than 1.0 WLM [AIF 1986]. The gamma radiation exposures of U.S. uranium miners are generally regarded to be less than the whole-body occupational exposure limit of 5 rem (50 mSv) per year [Breslin et al. 1969; Schiager et al. 1981].

F. Measurement Methods for Airborne Radon Progeny

1. Description of Measurement Methods

a. Grab Sampling Methods

Grab sampling methods for measuring airborne radon progeny involve drawing a known volume of air through a filter and counting the

Table 11-4.--Annual cumulative exposures of U.S. miners to radon progeny in 20 underground uranium mines during 1984^{*,†}

| Job category | Number of exposed workers by exposure range | | | | Total |
|--------------|---|-----------------|-----------------|-----------------|----------------|
| | 0-1.0 WLM | 1.01-2.0 WLM | 2.01-3.0 WLM | 3.01-4.0 WLM | |
| Production | 456 (62) [§] | 217 (29) | 48 (6) | 18 (2) | 739 (100) |
| Maintenance | 182 (91) | 19 (9) | 0 (0) | 0 (0) | 201 (100) |
| Management | 267 (79) | 62 (18) | 8 (2) | 0 (0) | 337 (100) |
| Service | 100 (78) | 23 (18) | 5 (4) | 0 (0) | 128 (100) |
| Total | 1,005 (72) | 321 (23) | 61 (4) | 18 (1) | 1,405 (100) |

*Adapted from data of the Atomic Industrial Forum [AIF 1986].

†Anyone who worked for more than one mine operator in 1984 would have been reported more than once.

§Figures in parentheses are the % of total.

alpha or beta radioactivity on the filter during or after sampling. Grab sampling methods used in underground mines are listed in Table 11-5.

In one-count grab sampling methods such as those used with instant working-level monitors, the radioactivity is determined over a single counting period using a scintillation counter. In two-count methods, the radioactivity is determined over two counting periods, and the ratio of these two measurements is used to calculate the radon progeny concentrations. In a three-count method, radon progeny concentrations are derived from the relative changes in the measurements taken at three 30-minute intervals.

Critically important factors are the proper calibration of radiation detectors and pumps, filters that precisely fit the equipment, and accurate maintenance of the flow rate during the sampling period. It is also important to prevent the accumulation of radionuclides to avoid contamination of the pump, counting equipment, and filters [Schiager et al. 1981].

Table II-5.--Grab sampling methods for radon progeny*

| Method | Reference | Description of method | Sampling time (min) | Flow rate (L/min) | Minimum time for sampling and analysis (min) |
|---|--------------------------|-----------------------|---------------------|-------------------|--|
| Kusnetz 5-40-2 | Kusnetz 1956 | One-count | 5 | 2 | 47 |
| Kusnetz 5-90-2 | Kusnetz 1956 | One-count | 5 | 2 | 97 |
| Rolle | Rolle 1972 | One-count | 10 | 2 | 19.4 |
| 3 R-WL [†] alpha Spectroscopy | Schiager 1977 | One-count | 2 | 2.5 | --- |
| Shreve [†] | Shreve 1976 | One-count | 2 | 2.5 | 3.5 |
| Shreve corrected | Shreve et al. 1977 | One-count | 2 | 2.5 | 3.5 |
| Shreve optimized | Holub 1980 | Two-count | 2 | 2.5 | 3.5 |
| Hill optimized | Holub 1980 | Two-count | 2 | 2 | 7.5 |
| James and Strong alpha ratio | James and Strong 1973 | Two-count | 5 | 10 | 11 |
| James and Strong optimized | Holub 1980 | Two-count | 5 | 10 | 11 |
| HBS | Holub 1980 | Two-count | 5 | 10 | 2 |
| Alpha spectroscopy | Borak et al. 1981 | Two-count | 2 | 2.5 | 2 |
| Tsivoglou and modified Tsivoglou | Tsivoglou et al. 1953 | Three-count | 5, 10, or 30 | 5-10 | --- |

*Adapted from Schiager et al. 1981.

[†]Used in an instant working level monitor.

Statistical uncertainties associated with the various grab sampling methods for radon progeny are presented in Table II-6. Data indicate that the relative precision of the methods is the same. The major differences are the total time period required for sampling and analysis, the capability of determining exposure concentrations at the work site, and the amount of routine maintenance and calibration required of the instrumentation.

b. Continuous Monitoring Methods

In continuous monitoring methods, air is sampled continuously, and (as with other methods) the alpha or beta radioactivities are determined over the length of the collection period. Continuous monitoring devices and systems have been described elsewhere [Haider and Jacobi 1973; Holmgren 1974; Drouillard and Holub 1977; Kawaji et al. 1981; Bigu and Kaldenbach 1984; Sheeran and Franklin 1984; Bigu and Kaldenbach 1985; Drouillard and Holub 1985]. The characteristics and statistical uncertainties for some continuous monitoring methods are presented in Table II-7.

The U.S. Bureau of Mines has designed an automated continuous monitoring system in which up to 768 detector stations can be linked to a central control unit. The system was designed to trigger an alarm when airborne radon progeny exceed a specified concentration [Sheeran and Franklin 1984]. Although continuous monitoring methods can provide a rapid estimate of exposure concentrations, placement of the instrumentation in active work areas is difficult and may not always be representative of the exposure in the miner's breathing zone.

c. Personal Dosimeters

Personal dosimeters for radon progeny are intended to automatically record a miner's cumulative exposure regardless of fluctuations in radon progeny concentrations. Thus these devices eliminate the need to document work area location and occupancy time. Although several personal dosimeters have been tested in U.S. uranium mines, none are in routine use in this country because of problems in calibration and lack of precision [Schiager et al. 1981].

1. Passive Dosimeters

Passive dosimeters rely on the natural migration of attached and unattached radon progeny to the detection area of the device without the use of an air pump. Thin plastic foils sensitive to alpha particles are used as detectors. Although passive dosimeters using track etch foils have been studied in underground mines [Domanski et al. 1982], such devices are still in the developmental stage [Schiager et al. 1981].

Table II-6.--Uncertainties associated with grab sampling methods for radon progeny*

| Method | Reference | Uncertainty in accuracy of method (%) | Uncertainty in precision of method (%) | | | Total combined uncertainty at 0.3 WL(%)† |
|---------------------------------|--------------------------|---|---|--------|---------|--|
| | | | 1.0 WL | 0.3 WL | 0.05 WL | |
| Kusnetz 5-40-2 | Kusnetz 1956 | 9 | 3.3 | 6.0 | 15 | 38 |
| Kusnetz 5-90-2 | Kusnetz 1956 | 10 | 5.1 | 9.3 | 23 | 39 |
| Rolle | Rolle 1972 | 20 | 1.4 | 2.6 | 12 | 41 |
| Shreve§ | Shreve 1976 | 15 | 2.8 | 5.1 | 13 | 39 |
| Shreve corrected | Shreve et al. 1977 | 6 | 2.8 | 5.1 | 13 | 38 |
| Shreve optimized | Holub 1980 | 4 | 3.0 | 5.5 | 25 | 37 |
| Hill optimized | Holub 1980 | 13 | 7 | 13 | 31 | 41 |
| James and Strong alpha ratio | James and Strong 1973 | 16 | 0.8 | 1.4 | 3.6 | 39 |
| James and Strong optimized | Holub 1980 | 13 | 1.5 | 2.7 | 6.7 | 39 |
| HBS | Holub 1980 | 6 | 1.4 | 2.6 | 6.3 | 37 |
| Alpha spectroscopy | Borak et al. 1981 | 16 | 1.1 | 2.0 | 4.5 | 39 |

*Adapted from Schiager et al. 1981.

†Contains the total combined uncertainty resulting from human error and errors in precision, accuracy, temporal changes in radon progeny concentration (WL), occupancy factor, and recordkeeping.

§Used in an instant working-level monitor.

Table II-7.—Summary of continuous monitoring methods for radon progeny*

| Detector | Reference | Activity measured | Flow rate (L/min) | Minimum counting time (min) | Combined uncertainty in precision and accuracy of K-method† at 1 WL(%) |
|----------------------|---------------------------|-------------------|-------------------|-----------------------------|--|
| Surface barrier | Drouillard and Holub 1977 | Alpha | 1-10 | 15 | 2.2 |
| Geiger-Mueller | Drouillard and Holub 1977 | Beta | 1-10 | 15 | 8.1 |
| Proportional counter | Kawaji et al. 1981 | Alpha | 1 | 15 | 3.6 |
| Geiger-Mueller | Schiager et al. 1981 | Alpha and Beta | 1-10 | 15 | --- |

*Adapted from Schiager et al. 1981.

†Precision is based on sampling air at 1 L/min for 15 min when the potential alpha energy is equivalent to 1 WL.

2. Active Dosimeters

Active dosimeters use a mechanical pump to draw a known volume of air through a filter. The alpha radiation emitted by the radon progeny collected on the filter is counted and recorded automatically. The following dosimeter detectors have been tested for use under mining conditions: thermoluminescent detectors [McCurdy et al. 1969; White 1971; Phillips et al. 1979; Southwest Research Institute 1980; Grealy et al. 1982], electronic detectors [Durkin 1977], and track etch detectors [Auxier et al. 1971; Zettwoog 1981; Bernhard et al. 1984]. Active track etch dosimeters are used for radiation monitoring in all underground mines in France [Schiager et al. 1981; Bernhard et al. 1984].

d. Factors to Consider When Selecting Measurement Methods

Concentrations of radon progeny have been reported to vary among the different uranium mines and work areas within each mine [Schiager et al. 1981]. These variations have been attributed to the type of mining process, the grade of ore mined, and the effectiveness of the ventilation to control exposures. Historically, radon progeny exposures in work areas were measured by grab sampling techniques that used the Kusnetz count method or by the instant working-level monitor. More recently, other methods such as continuous monitors and personal dosimeters have also been used in mines. Personal dosimeter methods are clearly more desirable, but they have not been rigorously tested in U.S. mines, and they have been reported to be unreliable for determining exposures over an 8- to 10-hr work shift [Schiager et al. 1981]. Continuous monitoring methods can rapidly detect changes in radon progeny concentrations and can be equipped with an alarm system that will be activated at preset concentrations. These monitors are often stationed at fixed locations within travelways, haulageways, shops, etc. because of the difficulty of moving and restationing them within active mine areas. Although these monitors do not usually provide adequate data for determining worker exposures, they can signal the occurrence of problems in the ventilation system and identify exposure sources.

NIOSH believes that the use of instant working-level monitors or the Kusnetz count method will provide reliable estimates of exposure to radon progeny. Other methods at least equivalent in accuracy, precision, and sensitivity can be used (see Table II-6). Any method chosen must be capable of meeting the sampling strategy requirements described in Appendix IV.

G. Respirator Selection and Credit for Respirator Use

1. Respirator Selection

Historically, NIOSH has recommended the use of the most protective

respirators* when workers are exposed to potential occupational carcinogens [NIOSH 1987]. Although cumulative exposure to radon progeny may result in cancer, the use of the most protective respirators may not always be technically feasible or safe in routine underground mining operations. Supplied-air respirators (SARs) that are NIOSH/MSHA-certified provide breathing air from compressors or a cascade system of air-supply tanks and are approved only for use with air lines less than 300 ft long. However, the use of SARs may not be practical in underground mining operations. The reasons are that it is difficult to provide sufficient quantities of breathing air through air lines over long distances and that the air lines are susceptible to crimping and severing from the movement of mining vehicles and haulage cars on tracks. Furthermore, many underground work areas and passageways in mines are too small and cramped with equipment to accommodate air compressors or large air-supply tanks. In addition to being cumbersome in underground mines because of their size, self-contained breathing apparatuses (SCBAs) weigh as much as 35 lb, and SARs weigh approximately 6 lb. Thus when SCBAs or SARs are worn for extended periods, their additional weight can also cause increased physiological burden in the form of heat stress [White and Ronk 1984a, 1984b; White and Hodous 1987; White et al. 1987].

Finally, NIOSH believes that the routine use of SCBAs and SARs may result in increased injuries in underground mining operations. NIOSH is not aware of any studies specifically dealing with injuries or other safety hazards associated with the use of SARs and SCBAs in mines. However, several studies have shown that obstacles introduced into the workplace result in a significantly increased risk of injury from tripping, slipping, or falling [National Safety Council 1981; Szymusiak and Ryan 1982a, 1982b]. Because mining is currently one of the most dangerous industries in the United States with regard to occupational deaths and injuries (MMWR 1987, BLS 1987), NIOSH believes that this problem would be exacerbated by the routine use of SCBAs and SARs.

NIOSH believes that there is sufficient safety and health evidence to recommend against the routine use of SARs and SCBAs for reducing exposure to radon progeny during underground mining operations.

Table 1-1 lists the respirators that NIOSH recommends for use against exposure to radon progeny. For average work shift concentrations of radon progeny that exceed 1/12 WL, the recommended respirators include air-purifying respirators with high-efficiency particulate air (HEPA) filters. The HEPA filter media are recommended by NIOSH for use with the air-purifying classes of respirators. These filters are the most

*Either (1) any self-contained breathing apparatus (SCBA) equipped with a full facepiece and operated in a pressure-demand or other positive-pressure mode, or (2) any supplied-air respirator (SAR) equipped with a full facepiece and operated in a pressure-demand or other positive-pressure mode in combination with an auxiliary SCBA operated in a pressure-demand or other positive-pressure mode.

efficient type of particulate filter available, and they are less susceptible than others to performance degradation resulting from humid storage and use conditions [Stevens and Moyer 1987].

2. Credit for Respirator Use

A miner's exposure to radon progeny may be less than the average work shift concentration in an area, depending on the class of respirator worn and the percentage of time the respirator is worn properly. This reduced exposure for miners who wear respirators can be calculated by dividing the average work shift concentration of radon progeny by the credit factor (CF) for that class of respirator (see Table I-1).

The credit factors in Table I-1 were determined by the following equation:

$$P_t = 1/CF = P_w \times t_w + P_n \times t_n$$

where P_t = the total penetration of radon progeny into the respirator facepiece.

APF = the assigned protection factor (a complete listing of the APFs for all classes of respirators can be found in the NIOSH Respirator Decision Logic [NIOSH 1987]).

CF = the credit factor

P_w = the penetration of radon progeny while wearing the respirator (i.e., 1/APF)

t_w = the proportion of time during the work shift that the miner wears the respirator properly

P_n = the penetration of radon progeny while not wearing a respirator properly (i.e., 100% or 1.0)

t_n = the proportion of time during the work shift that the miner does not wear the respirator properly (i.e., 1.0 - t_w)

An unpublished Canadian study evaluated the proportion of time during the work shift that a group of underground uranium miners properly wore their helmet-type, powered, air-purifying respirators [Linauskas and Kalos 1984; Kalos 1986]. This study revealed an effective utilization rate of 65%. Thus where the respirator utilization rate is unknown, NIOSH has chosen t_w equal to 0.65 and t_n equal to 0.35 for the calculation of CFs. Substituting the applicable values into the above equation yields the following:

$$\begin{aligned} P_t &= 1/CF = 1/APF \times t_w + 1.0 \times t_n \\ &= 1/CF = 1/APF \times 0.65 + 1.0 \times 0.35 \\ &= 1/CF = 0.65/APF + 0.35 \end{aligned}$$

Then rearranging terms yields

$$CF = APF / (0.65 + 0.35 APF)$$

The following calculations are for the CFs shown in Table I-1:

$$\text{For an APF of 5, } CF = 5 / [0.65 + 0.35(5)] = 2.1$$

$$\text{For an APF of 10, } CF = 10 / [0.65 + 0.35(10)] = 2.4$$

$$\text{For an APF of 25, } CF = 25 / [0.65 + 0.35(25)] = 2.7$$

$$\text{For an APF of 50, } CF = 50 / [0.65 + 0.35(50)] = 2.8$$

$$\text{For an APF of 1000, } CF = 1000 / [0.65 + 0.35(1000)] = 2.9$$

$$\text{For an APF of 2000, } CF = 2000 / [0.65 + 0.35(2000)] = 2.9$$

$$\text{For an APF of 10,000, } CF = 10,000 / [0.65 + 0.35(10,000)] = 2.9$$

If a mine operator can verify to MSHA that respirator utilization is greater than 65%, NIOSH recommends a recalculation of the CFs using this higher utilization rate. However, the highest utilization rate that NIOSH recommends is 90%. The CFs for these extremes of utilization rates are listed in Table I-1.

III. BASIS FOR THE RECOMMENDED STANDARD

A. Assessment of Effects

1. Human Studies

a. Association of Radon Exposure with Lung Cancer Mortality

Appendix I contains the report prepared by NIOSH and submitted to MSHA on May 31, 1985, entitled Evaluation of Epidemiologic Studies Examining the Lung Cancer Mortality of Underground Miners. Several of the epidemiologic studies evaluated in that report demonstrate an association between exposure to radon progeny and lung cancer mortality in underground uranium miners [Lundin et al. 1971; Sevc et al. 1976; Kunz et al. 1978; Waxweiler et al. 1981; Placek et al. 1983; Samet et al. 1984; Muller et al. 1985; Tirmarche et al. 1985]. The relationship between exposure to radon progeny and lung cancer mortality has also been observed in workers in underground metal mines [Wagoner et al. 1963], iron ore mines [Boyd et al. 1970; Jorgensen 1973 (updated in 1984); Damber and Larsson 1982; Edling and Axelson 1983; Radford and Renard 1984], tin mines [Fox et al. 1981; Jingyuan et al. 1981; Wang et al. 1984], fluorspar mines [Morrison et al. 1985], gold mines [Muller et al. 1985], and zinc/lead mines [Axelson and Sundell 1978]. In addition, some of these studies demonstrate a direct exposure-response relationship between lifetime cumulative exposure to radon progeny and lung cancer mortality [Lundin et al. 1971; Sevc et al. 1976; Kunz et al. 1978; Morrison et al. 1985; Muller et al. 1985].

Statistically significant standardized mortality ratios (SMRs)* above 400% were observed in three studies in which workers accumulated mean lifetime exposures above 100 WLM [Sevc et al. 1976; Kunz et al. 1978; Waxweiler et al. 1981; Morrison et al. 1985]. Statistically significant SMRs between 140% and 390% were observed in two other studies in which workers accumulated mean lifetime exposures below 100 WLM [Radford and Renard 1984; Muller et al. 1985] and in preliminary findings of a third study in which workers accumulated estimated mean lifetime exposures below 100 WLM [Tirmarche et al. 1985].

b. Synergistic Effects of Other Substances

Although the literature consistently demonstrates an association between lung cancer incidence and exposure to radon progeny, it is possible that some of the miners studied were exposed to other substances as well. These substances may have acted synergistically

*The standardized mortality ratio (SMR) is the ratio of the mortality rates of two groups being compared. This ratio is expressed as a percentage and is usually adjusted for age or time differences between the two groups.

with radon progeny to potentiate the effects of the radon exposure. [Doull et al. 1980]. Substances with synergistic potential include arsenic [NIOSH 1975a; Wang et al. 1984; Sevc et al. 1984], hexavalent chromium, nickel, cobalt [NIOSH 1975b; NIOSH 1977; Sevc et al. 1984]; serpentine [Radford and Renard 1984]; iron ore dust [Boyd et al. 1970; Jorgensen 1973, 1984; Damber and Larsson 1982; Edling and Axelson 1983; Pham et al. 1983; Radford and Renard 1984], and diesel exhaust [Wagoner et al. 1963; Boyd et al. 1970; Waxweiler et al. 1981; Fox et al. 1981; Damber and Larsson 1982; Edling and Axelson 1983; Jorgensen 1984; Sevc et al. 1984; Muller et al. 1985; Morrison et al. 1985; Tirmarche et al. 1985].

Risk analyses were performed on data from epidemiologic studies of U.S. uranium miners [Whittemore and McMillan 1983; Appendix II] and Swedish iron ore mine workers [Radford and Renard 1984]. These analyses indicate that the risk of mortality from lung cancer among miners who are exposed to radon progeny is greater among those who smoke cigarettes than those who do not smoke.

c. Relation of Lung Cancer Risk to Cumulative Radon Exposure

Since completion of the NIOSH report (Appendix I), Howe et al. [1986] published a study of surface and underground mine workers who had worked in Canada in the Eldorado Lodge Uranium Mine between 1948 and 1980. That cohort included 8,487 workers. Table III-1 describes their characteristics with respect to age, lifetime cumulative exposure, duration of employment, and type of mine work (surface or underground).

Table III-1.--Characteristics of mine workers employed at the Eldorado Lodge Uranium Mine during the period 1948-80

| Type of mine worker | Mean age at 1st employment | Mean lifetime cumulative exposure (WLM) | Mean duration of employment (months) | Miners in cohort | |
|-------------------------|----------------------------|---|--------------------------------------|------------------|---------|
| | | | | No. | % total |
| Surface only* | 27.7 | 2.8 | 22.2 | 4,077 | 48 |
| Surface and underground | --- | 28.9 | 43.9 | 572 | 7 |
| Underground | 28.8 | 16.6 | 15.0 | 3,838 | 45 |

*Never employed underground.

Sixty-five deaths from lung cancer were observed for the total cohort, but only 34.24 lung cancer deaths were expected on the basis of age-specific and calendar-year-specific Canadian national mortality rates (SMR = 190; $p < 0.05$). Workers with lifetime cumulative exposures greater than 5 WLM experienced 46 deaths from lung cancer as opposed to 15.88 expected deaths (SMR = 290; $p < 0.0001$).

In this study, Howe et al. [1986] estimated the annual average concentrations of radon progeny (WL) for the period 1954 through 1980 from measurements of radon gas and radon progeny. Samples of radon gas were collected from all areas of the mine from 1954 through 1967 to assess the effectiveness of dilution ventilation. Samples of radon progeny were collected several times per month per work site since 1967. These estimated values were used to assign annual exposure values (WLM) to the workers according to the number of hours worked underground. Howe et al. then subdivided the cohort into seven categories of WLM exposure: 0 to 4, 5 to 24, 25 to 49, 50 to 99, 100 to 149, 150 to 249, and greater than or equal to 250. Based on these stratified categories the risk of death from lung cancer increased linearly with increasing exposure. For the exposure categories of 5 to 24, 25 to 49, and 50 to 99 WLM, the relative risk was elevated, but the difference from the expected risk for an unexposed population was not statistically significant. For all exposure categories above 100 WLM, the relative risk was significantly elevated ($p < 0.05$); note, however, that the first 10 years of followup were excluded from this calculation. For the total cohort, the relative risk coefficient was 3.28% per WLM, and the absolute risk coefficient was 20.8 per 10^6 person-years per WLM (any excess mortality within the 10 years following initial exposure was excluded from this calculation).

Two additional epidemiologic studies that were not included in the 1985 NIOSH report (Appendix I) have also been reported. Pham et al. [1983] studied 1,173 iron mine workers in France who were aged 35 to 55 and who had normal chest X-rays at the beginning of the study period in 1975. Thirteen mine workers who had worked underground for a mean of 25.2 years died of lung cancer between 1975 and 1980; only 3.7 deaths were expected from an age-standardized comparison with French males for this same period (SMR = 351; $p < 0.05$). Although exposure records were not available, the authors estimated that some workers may have received lifetime cumulative exposures to radon progeny in the range of 100 to 150 WLM.

Solli et al. [1985] observed 318 niobium mine workers in Norway from 1953 through 1981; 77 of these miners were underground workers. This cohort experienced a total of 12 lung cancer deaths, though only 2.96 deaths were expected on the basis of age-specific rates for Norwegian males (SMR = 405; $p < 0.001$). The underground workers experienced 9 lung cancer deaths whereas only 0.81 were expected on the basis of age-specific rates for Norwegian males (SMR = 1,111; $p < 0.001$). From estimates of total exposure to alpha radiation (based on limited measurements of radon and thoron progeny taken in

1959), the authors determined that the risk of lung cancer increased significantly ($p < 0.05$) with increasing alpha radiation for the exposure categories of 1 to 19, 20 to 79, 80 to 119, and greater than or equal to 120 WLM. The excess absolute risk for those exposed workers was reported to be 50 per 10^6 person-years per WLM.

The epidemiologic studies of lung cancer mortality in mine workers exposed to radon progeny (including those studies discussed in Appendix I) are summarized in Tables III-2 and III-3.

2. Animal Studies

a. Effects of Exposure to Radon Progeny

Chameaud et al. [1984a] studied the effects of exposure to radon progeny in specific pathogen-free (SPF) Sprague-Dawley rats. A total of 1,800 rats were exposed to radon progeny for 1 to 3 hr per day for 14 to 82 days, yielding an accumulated exposure of 20 to 50 WLM. An additional 600 rats were unexposed. The lung cancer incidence in rats was reported to be directly proportional to their lifetime cumulative exposure to radon progeny. The authors concluded that the amount of radiation needed to double the natural incidence of lung cancer in these rats was 20 WLM. Reduced life spans were not observed for rats in any of the exposure groups.

b. Relation of Lung Cancer Incidence to Radon Progeny Exposure

Chameaud et al. [1981; 1984a] determined that the lifetime risk coefficient (uncorrected for life span shortening) for the induction of lung cancers in rats was approximately 140 to 850×10^{-6} per WLM for exposures ranging from 20 to 4,500 WLM (Table III-4). This is consistent with the lifetime risk coefficient for lung cancer in humans (150 to 450×10^{-6} per WLM) estimated by the International Commission on Radiological Protection (ICRP) [ICRP 1981]. As shown in Table III-4, lung cancer incidence in rats increased as cumulative exposure to radon progeny increased. In contrast, the lifetime risk of lung cancer per unit of exposure (WLM) decreased with increasing exposure. These findings agree with those of the NIOSH risk assessment (Appendix II), in which the lifetime cumulative risk of lung cancer per unit of exposure decreased as cumulative exposure increased in underground uranium mine workers.

c. Synergistic Effects of Cigarette Smoke

Chameaud et al. [1980, 1982] studied the ability of radon progeny to initiate lung cancer in groups of 50 SPF Sprague-Dawley rats that were subsequently exposed to cigarette smoke. The chamber concentrations of alpha radiation were 0, 300, and 3,000 WL; these concentrations yielded cumulative dose levels of 0, 100, 500, and 4,000 WLM, respectively, over a 2-month period for those groups of animals. Treatment groups were exposed to a total of 352 hr of cigarette smoke (9 cigarettes/500 L of air for 10 to 15 min per day, 4 days per week for 1 year. Exposure to radon progeny alone

Table III-2.--Summary of principal studies of lung cancer mortality in underground mine workers exposed to radon progeny

| Type of mine (location) | Reference | Mean lifetime cumulative exposure (WLM) | Person-years | Lung cancer deaths | | |
|--|--|---|------------------------|--------------------|----------------------|--------------------|
| | | | | Observed | Expected | SMR [†] |
| Uranium (U.S.) | Waxweiler et al. [1981] Lundin et al. [1971] | 821 [§] (median = 430) | 62,556 | 185 | 38.4 | 482 |
| Uranium (Czechoslovakia) [#] | Placek et al. [1983] [#] Kunz et al. [1978] [#] | 289 ^{**} | 56,955 | 211 | 42.7 | 496 |
| Uranium (Ontario, Canada) | Muller et al. [1985] | 40-90 ^{††} | 202,795 ^{††} | 82 ^{††} | 56.9 ^{††} | 144 ^{††} |
| Iron (Sweden) | Radford & Renard [1984] | 81.4 ^{§§} | 24,083 ^{§§} | 50 | 12.8 ^{§§} | 390 ^{§§} |
| Fluorspar (Newfoundland) | Morrison et al. [1985] | --- ^{###} | 37,730 ^{###} | 104 | 24.38 ^{###} | 427 ^{###} |
| Uranium (Saskatchewan, Canada) | Howe et al. [1986] | 16.6 ^{***} | 118,341 ^{†††} | 65 ^{†††} | 34.24 ^{†††} | 190 ^{†††} |

*Comparisons between these studies, especially for purposes of risk assessment, should be made with caution because of differences in the calculations of person-years, expected deaths, and SMR values in the various studies.

[†]p<0.05 except in Muller et al. [1985], Radford & Renard [1984], and Morrison et al. [1985]; because p-values were not provided in these three studies, they were estimated from the observed lung cancer deaths and the Poisson frequency distribution.

[§]Lifetime cumulative exposures ranged from less than 60 to greater than 3,720 WLM.

[#]Studies are of uranium mine workers who started work underground between 1948 and 1952.

^{**}Lifetime cumulative exposures ranged from less than 50 to approximately 1,000 WLM.

^{††}Values are for uranium mine workers with no previous gold mining experience; exposures were lagged up to 10 years; lifetime cumulative exposures ranged from 0.1 to greater than 340 WLM.

^{§§}Person-years for the first 10 years of mining experience were excluded; expected deaths were adjusted for smoking status; exposures were lagged 5 years; lifetime cumulative exposures ranged from 0 to greater than 200 WLM.

^{###}Person-years for surface and underground mine workers were included; person-years for the first 10 years of mining experience were excluded; radon progeny exposure levels were recently reestimated [Corkill and Dory 1984]; lifetime cumulative exposures ranged from 0 to greater than 2,040 WLM.

^{***}Value was based on underground workers (surface workers received a mean exposure of 2.8 WLM); lifetime cumulative exposures ranged from 0 to greater than 250 WLM.

^{†††}Values were based on surface and underground workers.

Table III-3.--Summary of additional studies of lung cancer mortality in underground mine workers exposed to radon progeny*

| Type of mine (location) | Reference | Estimated concentration or exposure | Comparison groups | Lung cancer deaths Observed/Expected | | Rate ratio [†] for lung cancer deaths |
|-------------------------------------|----------------------------|---|--|---|-------------------|---|
| Iron (Grangesberg, Sweden) | Edling and Axelson [1983] | 0.3 to 1.0 WL | Underground miners aged 50 and above vs. nonexposed individuals in the parish aged 50 and above | 33 | 2.87 [§] | 11.50 |
| Zinc-lead (Sweden) | Axelson and Sundell [1978] | 1 WL | Underground miners vs. non-exposed individuals in the parish | 21 | 1.28 [§] | 16.4 |
| Iron (Kiruna, Sweden) | Jorgensen [1973, 1984] | 0.5 WL | Underground miners vs. Swedish males | 28 | 9 | 3.11 |
| | | | Underground miners vs. Kiruna males | 28 | 6.79 | 4.12 |
| Iron (Kiruna and Gallivare, Sweden) | Damber and Larsson [1982] | 0.095 to 2.025 WL | Underground miners vs. non-exposed individuals in the Kiruna and Gallivare parishes | 20 | 2.74 [§] | 7.3 |
| Metal (U.S.) | Wagoner et al. [1963] | 0.05 to 0.40 WL | White male underground miners vs. white males from the same States | 47 | 16.1 | 2.92 |
| Uranium (U.S.) | Samet et al. [1984] | Lifetime exposure: 30 to 2,698 WLM; median exposure: 1,207 WLM (values are for 14 of 23 uranium miners) | Navajo males with uranium mining experience vs. Navajo males listed in the New Mexico tumor registry who died of cancer other than lung cancer | 23 | 0 | NA [#] |
| Tin (Cornwall, United Kingdom) | Fox et al. [1981] | 1.2 to 3.4 WL | Underground miners vs. English and Welsh males | 28 | 13.27 | 2.11 |

*These studies contain limitations in study design, radon progeny exposure records, smoking history information, followup, etc. Comparisons between these studies, especially for the purposes of risk assessment.

[†]p<0.05 (some p-values were estimated from the observed lung cancer deaths and the Poisson frequency distribution); rate ratios depend on lung cancer mortality in the comparison population and are sensitive to error in rates that are based on a small number of expected deaths.

[§]The expected number of deaths was estimated from the rate ratios provided by the authors.

[#]Not applicable. The 95% confidence limits of the rate ratios range from 14.4 to infinity.

Table III-4.--Radon progeny exposure and risk of lung cancer in specific, pathogen-free Sprague-Dawley rats*

| Lifetime cumulative exposure (WLM) | Number of rats exposed | Number of rats with lung cancer | Percentage of rats with lung cancer | Lifetime lung cancer risk coefficient ($10^{-6}/\text{WLM}$) [†] |
|------------------------------------|------------------------|---------------------------------|-------------------------------------|---|
| 2 [§] | 600 [§] | 5 [§] | 0.83 [§] | --- |
| 20-25 | 1,000 | 23 | 2.3 | 850 |
| 50 | 794 | 30 | 3.8 | 580 |
| 290 | 21 | 2 | 9.5 | 330 |
| 860 | 20 | 4 | 20.0 | 280 |
| 1,470 | 20 | 5 | 25.0 | 170 |
| 1,800 | 50 | 17 | 34.0 | 180 |
| 1,900 | 20 | 7 | 35.0 | 180 |
| 2,100 | 54 | 23 | 42.6 | 200 |
| 2,800 | 180 | 76 | 42.2 | 150 |
| 3,000 | 40 | 17 | 42.5 | 140 |
| 4,500 | 40 | 29 | 72.5 | 160 |

*Adapted from Chameaud et al. 1981, 1984a.

[†]Values were not corrected for life span shortening.

[§]Values are for rats in control group.

demonstrated a directly proportional dose-effect relationship for induction of cancer (500 and 4,000 WLM). However, when a similar period of radon exposure was followed by exposure to cigarette smoke, a dose-related, twofold to fourfold increase occurred in lung cancer incidence. The authors stated that the groups receiving high and medium doses of radon and cigarettes had cancers that were not only larger but were more invasive and metastatic compared with the groups exposed to radon alone. Conversely, neither the cigarette smoke alone nor the low-dose radon progeny exposure (100 WLM) alone induced lung cancer.

In a parallel lifetime study, Chameaud et al. [1981] related the sequence of exposure to radon progeny and cigarette smoke to the

incidence of lung tumors (cancer incidence was not specified) in groups of 50 SPF Sprague-Dawley rats. One group of rats was exposed to radon progeny only (a cumulative exposure of 4,000 WLM); a second group was exposed first to cigarette smoke and then to radon progeny (4,000 WLM); a third group was exposed to radon progeny (4,000 WLM) and then to cigarette smoke; and a fourth group was exposed to cigarette smoke only. Similar incidences of tumors were observed among the rats exposed to radon progeny only (10 tumors) and those exposed first to cigarette smoke and then to radon progeny (8 tumors). In contrast, when the exposure to radon progeny preceded the exposure to cigarette smoke, the effect was potentiated--that is, 32 rats developed tumors. As stated previously, none of the rats exposed to cigarette smoke only developed lung cancer. No statistical analyses were performed on the results of this study.

d. Significance of Animal Studies

Life span experiments in animals exposed to radon progeny alone have demonstrated that increasing exposures produce increasing incidences of lung cancer. This finding is similar to those of the epidemiologic studies cited in the preceding section (III, A, 1). Because epidemiologic data are available, these animal data contribute relatively little to the final assessment of risk in humans or to the determination of an REL for exposure to radon progeny. Thus this document discusses only selected animal studies of the carcinogenic potential of radon progeny. Other studies have examined the sequential or concomitant exposures of rats, dogs, and hamsters to substances other than radon progeny (e.g., uranium ore dust, thorium, and tobacco smoke). Several additional studies (critiqued but not described in this document) confirm the adverse health effects of radon progeny on exposed animals [Chameaud et al. 1974, 1984b; Filipy et al. 1977a, 1977b; Gaven et al. 1977; PNL 1978; Cross et al. 1981, 1982a, 1982b, 1983, 1984; Cross 1984]. These animal studies generally confirm the risk of lung cancer reported among workers exposed to radon progeny.

B. Risk Assessment

NIOSH studied the lung cancer risk of uranium miners by using data from a U.S. Public Health Service (USPHS) study [Lundin et al. 1971] of white male uranium mine workers from the Colorado Plateau area (Colorado, Arizona, New Mexico, and Utah). That NIOSH risk assessment is described in a report entitled Quantitative Risk Assessment of Lung Cancer in U.S. Uranium Miners, which is reproduced in Appendix II. Appendix I contains a detailed discussion of the USPHS data.

In the NIOSH risk assessment, data were analyzed for 3,346 workers who had been followed from 1950 through 1982. By 1982, 1,215 workers had died; 256 of these deaths (21.1%) were due to lung cancer. A generalized version of the Cox proportional hazards model was used to estimate the relative risk of death resulting from lung cancer over a 30-year working lifetime at several cumulative exposure values. (The 30-year working lifetime was

selected to maintain consistency with the working lifetime commonly described by MSHA.) Relative risk is defined as the ratio of lung cancer mortality in a selected exposed group to lung cancer mortality in a comparison group. The quantitative risk assessment model presented in Appendix II did not include the length of time since the end of the mining exposure, which is a significant predictor of relative risk. This term was subsequently added to the generalized Cox model, and new parameter estimates were computed. The estimates in Tables III-5 and III-6 are based on this model. The major difference between the two quantitative risk assessment models is that under the new model, the relative risk estimates increase more rapidly during exposure and decrease more rapidly after exposure.

The risk of death resulting from lung cancer increased with increasing lifetime cumulative exposure to radon progeny (Table III-5); this finding is consistent with Appendix II. This direct relationship has been observed in previous epidemiologic studies [Lundin et al. 1971; Sevc et al. 1976; Kunz et al. 1978; Morrison et al. 1985; Muller et al. 1985]. As shown in Table III-5, the relative risk of 1.57 at 30 WLM corresponds to an average exposure of 1 WLM per year for a working lifetime of 30 years.

Table III-5.--Relative risk estimates of lung cancer at age 60 by annual and lifetime cumulative exposures to radon progeny

| Annual mining exposure above background (WLM/year) | Cumulative exposure* (WLM over a 30-year working lifetime) | Relative risk† | 95% confidence limits |
|--|--|----------------|-----------------------|
| 0.5 | 15 | 1.31 | 1.23 - 1.39 |
| 1.0 | 30 | 1.57 | 1.42 - 1.74 |
| 2.0 | 60 | 2.04 | 1.74 - 2.40 |
| 3.0 | 90 | 2.45 | 2.00 - 2.99 |
| 4.0 | 120 | 2.81 | 2.23 - 3.56 |

*Values are exclusive of background exposure.

†Estimates are based on a log-relative risk model fitted to age at initial exposure, time since cessation of exposure, and the natural logarithms of the following variables: cumulative mining and background exposure to radon progeny, cumulative cigarette smoking and background smoking, and rate of exposure to radon progeny.

Table III-6.--Estimated excess lung cancer deaths per 1,000 miners* resulting from 30 years of occupational exposure to radon progeny

| Annual mining exposure above background (WLM/year) | Total mining exposure (WLM) | Estimated excess lung cancer deaths per 1,000 miners | | |
|--|-----------------------------|--|--|-------|
| | | Point estimate | Approximate 95% confidence limits [†] | |
| | | | Lower | Upper |
| 4.0 | 120.0 | 42.0 | 25.0 | 71.0 |
| 3.0 | 90.0 | 32.0 | 19.0 | 54.0 |
| 2.0 | 60.0 | 22.0 | 13.0 | 36.0 |
| 1.0 | 30.0 | 10.0 | 7.0 | 17.0 |
| 0.5 | 15.0 | 4.9 | 3.4 | 7.6 |

*Estimates are based on a log-relative risk model fitted to age at initial exposure, time since cessation of exposure, and the natural logarithms of the following variables: cumulative mining and background exposure to radon progeny; cumulative cigarette smoking and background smoking; and rate of exposure to radon progeny.

[†]The approximate 95% confidence limits were calculated by applying the parameters from the quantitative risk assessment model together with their variances and covariances to the lung cancer mortality rates in the Colorado Plateau using an actuarial approach.

In addition to receiving workplace exposures to radon progeny, workers were assumed to have received average environmental exposures of 0.4 WLM/year. This is the value derived in the NIOSH risk assessment that led to the best fit of the model to the data. This assumed value is consistent with estimates of exposure to radon progeny for persons living near ore-bearing lands in the United States [NCRP 1975; Brookins 1986]. The average non-occupational exposure to radon progeny from natural geologic sources for persons in the United States is approximately 0.2 WLM/year [NCRP 1984b].

Relative risk modeling is common in the epidemiologic literature (especially in studies with lengthy followup) because the dramatic changes that occur in mortality rates with age and calendar year make absolute risk models extremely complicated. Most relative risk models assume that mortality rates in exposed populations are roughly proportional to the rates in unexposed populations at all ages and calendar periods. Because this assumption often approximates reality over a broad range of ages and calendar periods, the relative risk model can be expressed in a less complex form than absolute risk models (i.e., the relative risk model can be expressed without terms involving age and calendar year).

Excess lifetime risk estimates for lung cancer mortality have been generated (Table III-6) by applying the relative risk estimates in Table III-5 (see also Appendix II) to the lung cancer and all-causes mortality rates for

white males in the Colorado Plateau States. Excess risk is defined as the arithmetic difference between the risk of lung cancer mortality in a selected exposed group and the risk of lung cancer mortality in an unexposed comparison group.

The estimated excess lung cancer deaths (i.e., excess lifetime risk) in Table III-6 were computed by approximating the average of the exposure-determined relative risk function over 5-year age intervals spanning an entire lifetime. These average relative risks and the corresponding mortality rates for lung cancer and for all causes of death among white males in the Colorado Plateau were used to compute the probability of lung cancer mortality during a lifetime using the National Academy of Sciences actuarial method [NAS 1987].

It is important to understand the limitations of these risk estimates when examining the values in Table III-6. These limitations include the following:

- A relatively small portion of the cohort had the observed lower levels of cumulative occupational exposure, and the ability to generate precise point-risk estimates at the lower range of occupational exposure is not as strong. Only 7% of the workers in the cohort had lifetime cumulative exposures below 30 WLM, and only 7 of the 256 lung cancer deaths occurred among workers with lower cumulative exposures.
- The reliability of these excess lifetime risk estimates depends on (1) the accuracy of the original relative risk estimates and (2) the appropriateness of using lung cancer rates for the general white male population in the Colorado Plateau as an estimate of the background lung cancer rate (i.e., that which would occur in populations exposed only to background levels of radon progeny). This cohort contained no unexposed mine workers from which to estimate background lung cancer rates. Although certain limitations exist in using this type of rate [Monson 1980], background lung cancer mortality rates from the general U.S. white male population were used to estimate the background rates for the cohort.
- The background lung cancer rates were not corrected for cigarette smoking. However, the relative risk estimates used to calculate the lifetime risk estimates were adjusted for smoking. This implies that the lifetime risk estimates are only appropriate for a population with a pattern of smoking similar to that of the white male population of the Colorado Plateau.

In developing its recommendations, NIOSH has attempted to compare the risk of occupational exposure to radon progeny with the risk of background exposure in homes (i.e., exposure accruing outside the mining environment). The estimated average background exposure to radon progeny is approximately 0.2 WLM per year for the general U.S. population; this estimate is higher in the vicinity of radiation-emitting ore bodies [NCRP 1975]. The NIOSH risk assessment (Appendix II) indicated that 0.4 WLM per year was the background exposure value that led to the best fit of the model to the data. Data are

not available on actual background exposures (i.e., exposures accruing outside the mining environment) of underground miners in the Colorado Plateau, but background exposures probably vary substantially. No risk assessment has been completed on the lung cancer risk associated with background exposures for the general U.S. population or for the population living in the Colorado Plateau. Until studies in homes are completed, it will be impossible to directly contrast risk estimates for occupational exposures with those for background exposures in homes.

Currently it is not possible to compare the risk of occupational exposure with the risk of background exposure in homes. Nonetheless, it is important to consider occupational risk in the context of the background lung cancer risk. On the basis of State vital statistics records, NIOSH estimates that the lifetime risk of lung cancer in the Colorado Plateau, uncorrected for smoking, is approximately 45 lung cancers per 1,000 white males. Unfortunately, accurate lung cancer rates are not available for nonsmokers in the Colorado Plateau.

Given this value for background lung cancer risk, another question that must be considered is to what level it would be reasonable to control occupational risk. In its benzene decision, the U.S. Supreme Court gave the following example as the basis for evaluating the occupational risk of chemically induced leukemia: An exposure associated with 1 excess death per million exposed persons might pose an acceptable risk, whereas an exposure associated with 1 excess death per 1,000 exposed persons would pose a significant risk that should be reduced. This example is useful, but it cannot be strictly applied in all cases because it was offered as an illustration and not a fixed rule. In the specific case of lung cancer risk associated with radon progeny exposure, the example cannot be strictly applied because the background risk of lung cancer is much greater than the risk of leukemia at background exposure levels and because cigarette smoking is known to create a confounding effect that greatly increases risk. An excess of 1 lung cancer death per 1,000 would probably not be detectable in a general population if data were subject to considerable uncertainty, since it would necessitate differentiating between 46 and 45 deaths per 1,000.

Another important consideration is the technical feasibility of a given exposure limit. As stated earlier, NIOSH has determined that a cumulative exposure limit of 1 WLM per year is achievable (though some argue that it is not feasible on the basis of economics or current technology). NIOSH has found no evidence that any cumulative exposure lower than 1 WLM per year is feasible. As shown in Table III-6, the occupational exposure limit required to reduce expected lifetime risk to 1 excess lung cancer death per 1,000 miners is approximately 0.1 WLM per year. This cumulative exposure would require an occupational exposure concentration that is less than the concentration associated with a cumulative background exposure of 0.4 WLM per year, assuming background exposure is acquired outside the occupational environment. An occupational exposure limit of 0.1 WLM per year would therefore require average mine concentrations lower than the estimated background exposure concentrations.

In view of the preceding factors, the level of uncertainty in available data, and the apparent unfeasibility of limiting cumulative exposures to

less than 1.0 WLM per year, it does not seem reasonable to recommend exposure limits that would yield only 1 excess lung cancer death per 1,000 miners. NIOSH has determined that an exposure limit of 1 WLM is feasible in some mines and that such an exposure limit would substantially reduce risks from those associated with the current MSHA standard. An REL of 1 WLM per year is therefore recommended to substantially reduce risk and to stimulate the implementation and development of engineering and mining techniques to reduce exposure. The enforcement of this recommendation combined with additional health and developmental research may facilitate future exposure reductions and thereby reduce lung cancer risk.

C. Technical Feasibility

In a report to the U.S. Bureau of Mines, Bloomster et al. [1984a] analyzed the technical feasibility of reducing the airborne concentrations of radon progeny in underground uranium mines. The study included data from 14 underground uranium mines operating during the study period (September 1981 to May 1984). The authors concluded that some mines could operate at an annual exposure standard of 2 WLM by using dilution ventilation alone if it was introduced early in the development of the mine and if no contamination of inlet air was present. An extensive engineering analysis of 2 of the 14 mines indicated that it might be feasible to meet an operating standard of 1 WLM by using dilution ventilation in combination with other control methods such as bulkheading, air filtration, and use of sealants. The authors expressed doubt about the technical feasibility of operating these uranium mines at a standard of 0.5 WLM. Appendix III provides descriptions of engineering control methods that may be useful in underground mines.

D. Recommendations

Several schemes exist for identifying and classifying a substance as a carcinogen. For example, the National Toxicology Program (NTP) [NTP 1984], the International Agency for Research on Cancer (IARC) [WHO 1979], and the Occupational Safety and Health Administration (OSHA) [29 CFR 1990, Identification, Classification, and Regulation of Potential Occupational Carcinogens (also known as "The OSHA Cancer Policy")] have all considered this problem. NIOSH considers the OSHA classification the most appropriate for use in identifying potential occupational carcinogens and supports the following definition:

A "potential occupational carcinogen" is any substance, or combination or mixture of substances, which causes an increased incidence of benign and/or malignant neoplasms, or a substantial decrease in the latency period between exposure and onset of neoplasms in humans or in one or more experimental mammalian species as the result of any oral, respiratory, or dermal exposure, or any other exposure which results in the induction of tumors at a site other than the site of administration [29 CFR 1990.103].

This definition also includes any substance that mammals may potentially metabolize into one or more occupational carcinogens.

The epidemiologic data examined by NIOSH demonstrates that occupational exposure to radon progeny in underground mines has the potential for causing lung cancer in miners (see Appendix I) [Pham et al. 1983; Solli et al. 1985; Howe et al. 1986]. These human data are supported by a number of studies in which various animal species exposed to radon progeny also developed lung cancer [Chameaud et al. 1974, 1980, 1981, 1982, 1984a, 1984b; Filipy et al. 1977a, 1977b; Gaven et al. 1977; PNL 1978; Cross et al. 1981, 1982a, 1982b, 1983, 1984; Cross 1984]. Furthermore, the NIOSH risk assessment presented in Appendix II, which was based on the human studies, clearly demonstrates that a relationship exists between cumulative radon progeny exposure and the risk of developing lung cancer. The risk assessment shows that as cumulative exposure decreases, the risk of developing cancer decreases.

In arriving at an REL, NIOSH attempts to identify that exposure at which no worker will suffer material impairment of health or functional capacity. In the case of radon progeny, this task is difficult because the NIOSH risk assessment shows that even with an exposure of 0.5 WLM per year (15 WLM for a 30-year cumulative exposure) or below, the risk of developing lung cancer increases (see Table III-4 and Appendix II).

These results indicate that NIOSH should recommend an annual cumulative exposure limit well below 0.5 WLM, but NIOSH must also consider the technical feasibility of the REL. In previous NIOSH recommendations for the control of carcinogens, technical feasibility has often been interpreted as the ability to quantitate exposure; however, those recommendations were intended for use by nonmining industries where product substitution and engineering and process controls are generally more feasible.

Data from 1984 indicate that 94.4% of the workers in U.S. underground uranium mines accumulated annual radon progeny exposures of less than 2 WLM [AIF 1986]. Information obtained from the Bureau of Mines [Bloomster et al. 1984a] indicates that it is now technically feasible to achieve an annual radon progeny concentration of 1.0 WLM. NIOSH therefore recommends that cumulative exposure to radon progeny be limited to 1.0 WLM per year. This recommendation is intended to protect the health of America's underground miners, but it is tempered by the fact that currently it is not technically feasible to achieve annual exposures lower than 1.0 WLM using work practices and engineering controls.

To meet the NIOSH recommendation for an annual cumulative exposure of 1 WLM and to assure that mining is a viable year-long occupation, NIOSH believes that the daily average work shift concentration of radon progeny should not exceed 1/12 WL in any work area. Although adherence to the NIOSH REL will significantly reduce the risk of lung cancer in underground mine workers, it will not eliminate it.

No effective medical procedure currently exists to treat lung cancer caused by exposure to radon progeny. Furthermore, it has been demonstrated that exposure to both radon progeny and tobacco smoke result in a combined lung cancer risk that is greater than the risk posed by radon progeny or smoke alone. Thus it should be noted that the interaction between radon progeny and smoking is at a minimum additive, and more likely multiplicative. Cigarette smoking should therefore be emphasized as an even greater

detriment to mine workers exposed to radon progeny than it is to the general public. The implementation of smoking cessation programs should reduce the incidence of lung cancer in underground mine workers.

Because radon progeny are ubiquitous, exposure cannot be totally eliminated. For U.S. residents, the average annual nonoccupational exposure to radon progeny from natural geologic sources is approximately 0.2 WLM, and annual occupational exposures may be considerably higher. The REL of 1 WLM per year is not designed for the population at large, and no extrapolation is warranted beyond occupational exposures in underground metal or nonmetal mines. The REL is designed only for the radon progeny exposures of underground metal and nonmetal mine workers as applicable under the Federal Mine Safety and Health Act of 1969 [Public Law 91-173], as amended by the Federal Mine Safety and Health Act of 1977 [Public Law 95-164].

IV. RESEARCH NEEDS

The following research is needed to further reduce the risk of lung cancer development from occupational exposure to radon progeny.

A. Epidemiologic Studies

Needs for epidemiological studies have been identified as follows:

- A need exists for a followup study of the U.S. miner cohort from the original Public Health Service study to explore the risk of lung cancer among nonsmoking miners exposed to low concentrations of radon progeny. NIOSH is currently resurveying this cohort to update exposure histories and gather additional information on smoking behavior, dietary practices, and tumor cell types.
- A study is needed to determine whether radon gas itself or other contaminants that might be found in uranium mines are associated with increased morbidity and mortality.
- An epidemiologic study of injuries is needed in the mining industry to identify safety-related problems, since this industry has one of the highest injury rates in the United States. Particular emphasis should be given to whether or not respirator use is associated with an increased injury and health risk. This investigation should examine slips, trips, falls, and heart attacks.

B. Engineering Controls and Work Practices

Research should be conducted to develop more effective control technology methods for reducing exposure to radon progeny to less than 1 WLM. A control technology assessment of the uranium mining industry will assist in this effort by examining existing state-of-the-art technologies and work practices and by recommending new methods for controlling exposure to radon progeny.

C. Respiratory Protection

The following two types of research are recommended for respiratory protection:

- Research should be conducted to determine the extent of gamma radiation emitted from particles trapped on high-efficiency particulate air (HEPA) filters used on air-purifying respirators.
- A study should also be conducted to evaluate the physiological stress placed on miners who must wear respiratory protection. This study should be conducted both in the laboratory and in the mines.

D. Environmental (Workplace) Monitoring

Studies needed for environmental (workplace) monitoring are as follows:

- Research should be conducted to characterize and evaluate the importance of particle size, unattached fraction, and condensation nuclei concentrations in estimating the bronchial dose of radon progeny. The dose of alpha radiation affecting the bronchial airways depends on the size of the particles to which it is attached. Recent studies have shown that as particle size decreases, the concentration of radon progeny increases.
- Continued research is also needed to determine which factors affect the equilibrium between radon progeny and radon gas in mines. These studies should examine how such information may be used to predict the extent of exposure to radon progeny. Additional development and field testing of personal sampling devices is also needed for more complete determination of a miner's daily exposure.

PUBLIC HEALTH PERSPECTIVE

V. PUBLIC HEALTH PERSPECTIVE

In developing this document, NIOSH has been challenged to carefully consider all of the Institute's legislative, scientific, and moral responsibilities. Two legislative mandates are important in understanding NIOSH's responsibilities in developing this document and the recommendations it contains. First, the Occupational Safety and Health Act of 1970 [Public Law (PL) 91-596], which established NIOSH, requires safe and healthful working conditions for every working person. The Act further requires NIOSH to preserve our human resources by providing medical and other criteria that will ensure, insofar as practicable, that no worker will suffer diminished health, functional capacity, or life expectancy as a result of work experience [PL 91-956, Section 6(b)(5)]. The Act also authorizes NIOSH to develop new recommended criteria to further improve working conditions [PL 91-596, Sections 22(c) and (d)]. In addition, the Federal Coal Mine Health and Safety Act of 1969 [PL 91-173] and the Federal Mine Safety and Health Amendments Act of 1977 [PL 95-164] require NIOSH to develop and revise recommended occupational safety and health standards for mine workers. The Secretary of Health, Education, and Welfare (now the Secretary of Health and Human Services) shall consider, "in addition to the attainment of the highest degree of health protection for the miner . . . the latest available scientific data in the field, the technical feasibility of the standards, and experience gained under this and other health statutes" [PL 91-173, Title 1, Section 101(d)].

NIOSH has been required to review diverse scientific data that are subject to uncertainty and then, in keeping with its mandates, to recommend criteria that will attain the highest level of health protection and will at the same time account for other factors such as technical feasibility and insights gained through research and development.

To develop a public health perspective on the risk posed by occupational exposure to radon progeny, NIOSH must weigh a number of factors, as follows.

1. Human and animal data both clearly establish that exposure to radon progeny increases the risk of lung cancer. The human data consist of a number of positive epidemiologic studies, several of which demonstrate an exposure-related health risk that is not accounted for by smoking behavior. The animal studies demonstrate that lung cancer risk increases with exposure in the absence of smoking. It is important to note that smoking by miners appears to greatly exacerbate the risk of lung cancer posed by exposure to radon progeny alone.
2. The NIOSH risk assessment, based on a USPHS study of uranium miners [Lundin et al. 1971], demonstrated a significant exposure-response relationship. This analysis indicates that exposure to radon progeny at the current MSHA occupational exposure limit of 4 WLM over a working lifetime will result in 42 excess lung cancers per thousand miners. A miner's working lifetime has been defined as 30 years (MSHA uses 30 years as a miner's working lifetime). Risk declines substantially if a lower annual cumulative exposure is received over the working lifetime. Any risk assessment is subject to uncertainty because risk assessment

models may not reflect risk in a completely reliable way and because the data on which they are based are subject to uncertainties and limitations.

The Cox proportional hazards model, which was chosen for the NIOSH risk assessment, is considered one of the strongest analytical approaches for longitudinal epidemiologic data. But it is not clear how accurately the data can be extrapolated to predict risk below the levels of observed exposure. Current biological theory hypothesizes that carcinogenic processes involve an initiation stage that is followed by other stages before an actual malignancy is established. The essential characteristics of all of these stages remain to be delineated. The Cox proportional hazards model is very powerful in describing human risks based on epidemiologic data. Its strength is partly due to the model's ability to accommodate long follow-up periods during which changes occur in some of the risk factors, e.g., cumulative exposure. Nevertheless, it is not clear how accurately the Cox model or any other risk assessment model predicts the risk from a multistage cancer process when exposures are below levels that have been studied.

The USPHS study [Lundin et al. 1971] on which the NIOSH risk assessment was based is an extensive study, but the risk assessment is subject to uncertainties and limitations because of the nature of the data. For example, more uncertainty would be inherent in the risk estimates at the lower range of exposure because a relatively small proportion of this study population received the lowest cumulative exposures. Approximately 7% of the USPHS uranium miners (which included 7 lung cancers) had received cumulative occupational exposure levels of 30 WLM or less. At lower cumulative exposure levels, even smaller proportions of the cohort and fewer lung cancers were represented. Thus point estimates at these lower cumulative exposure levels would be more subject to the influence of chance occurrences. In addition, exposure levels are subject to measurement error. The uncertainty of exposures have been estimated to range from a relative standard deviation of 38% [Schaiger et al. 1981] to as high as 97% (see Appendix II).

3. Radon progeny and its associated risk are present in our ambient environment as well as in the mining environment and cannot be totally eliminated. Radon progeny are ubiquitous in that they emanate from all ore-bearing deposits containing elements that decay to produce radon gas. The national average exposure to radon progeny has been estimated to be 0.2 WLM [NCRP 1975]. Areas containing large amounts of ore-bearing deposits (e.g., the Colorado Plateau) are likely to have higher-than-average background levels of radon progeny [NCRP 1975]. The NIOSH risk assessment uses a fitted estimate of 0.4 WLM as the background exposure (the average annual cumulative exposure incurred in nonoccupational environments) in the Colorado Plateau. Although no adequate measurement data are available to characterize the level and variability of exposure in the homes of the general population and of miners, it is clear that everyone is exposed and that the degree of exposure depends on each individual's home and work environment. The limits of concentration detection and the accuracy of the measurement techniques become a potential problem when quantifying the very low

radon progeny exposure and concentration levels that may be found in the ambient environment (these levels are generally much lower than those found in underground mining environments). Extrapolation of risk to such low levels would become even more problematic than at higher levels because of the reduced accuracy of measuring such concentration levels. The elimination of radon progeny from the ambient and mining environments is not possible.

The primary engineering method for controlling radon progeny exposure is dilution ventilation. However, if radon progeny are ubiquitous in our ambient environment, no source of air is free of contamination. The only protective equipment that would eliminate exposure to radon progeny is the self-contained breathing apparatus (SCBA). SCBAs are unacceptable for wear in the ambient environment and represent a significant safety hazard if worn extensively in the mining environment.

4. It is valuable to compare the lung cancer risks associated with the miner's occupational and background exposures. No assessment has yet been made of the lung cancer risk associated with background exposures, either for the general U.S. population or for the population living in the Colorado Plateau. Until studies in homes are completed, it will be impossible to directly contrast the risks of occupational and background exposures.

Nonetheless, it is important to consider occupational risk in the context of the lung cancer risk experienced by the general population. On the basis of State vital statistics records, NIOSH estimates that the lifetime risk of lung cancer in the Colorado Plateau, uncorrected for smoking, is approximately 45 lung cancers per 1,000 white males. Unfortunately, accurate lung cancer rates are not available for nonsmokers in the Colorado Plateau.

Given this value for the lung cancer risk of background exposure, another question that must be considered is to what level it would be reasonable to control occupational risk. In its benzene decision, the U.S. Supreme Court gave the following example for the basis of evaluating occupational risk of chemically induced leukemia. The example indicated that an exposure associated with 1 excess death per 1 million exposed persons might pose an acceptable risk, whereas an exposure associated with 1 excess death per 1,000 exposed persons would pose a significant risk that should be reduced. This example is useful but it cannot be strictly applied in all cases, since it was offered as an illustration and not a fixed rule. In the specific case of lung cancer risk associated with radon progeny exposure, the example cannot be strictly applied because the risk of lung cancer is much greater than the risk of leukemia at background exposure levels and because cigarette smoking is known to create a confounding effect that greatly increases risk. An excess of 1 lung cancer death per 1,000 would probably not be detectable in a general population if the data were subject to considerable uncertainty, since it would necessitate differentiating between 46 and 45 deaths per 1,000.

5. The technical feasibility of achieving lower exposure levels is subject to the limitations of available technology. A report commissioned by the Bureau of Mines [Bloomster et al. 1984a, 1984b] has been the primary source for NIOSH's assessment of the technical feasibility of lower exposure levels. On the basis of an extensive engineering analysis of two uranium mines, these investigators indicated that it might be feasible to meet an operating standard of 1 WLM using the best available engineering controls. They expressed doubt about the technical feasibility of operating these uranium mines at a standard of 0.5 WLM. This analysis has been used by NIOSH to define exposure limits that are technically achievable with the best available technology.

These are some of the issues that have been considered by NIOSH in developing a recommended standard to prevent lung cancer associated with exposure to radon progeny. This process of weighing risk from a public health perspective parallels the philosophy of risk presented in the 1985 document entitled Risk Assessment and Risk Management of Toxic Substances: A Report to the Secretary [CCERP 1985]. In the process of developing this public health perspective, NIOSH has performed the following actions:

- NIOSH has identified a public health hazard posed by an occupational exposure. Exposure to radon progeny that occurs in underground mines and the ambient environment has been shown to cause a significant increase in lung cancer among uranium and other underground miners.
- NIOSH has developed recommendations in a manner that is prudent and in concert with the public need. This process was accomplished by complying with the Institute's legislative mandates to attain the highest level of health protection and at the same time consider other factors such as technical feasibility.
- NIOSH has sought appropriate public participation by eliciting external reviews. Reviews were requested from more than 60 individuals or groups, including industry, labor, academia, and government representatives. NIOSH has received and considered the comments from more than 30 of these reviewers.
- NIOSH has communicated risk understandably to both experts and lay persons. NIOSH has expressed risk as relative risk, which most epidemiologists and biostatisticians believe to be the most appropriate mode of expressing human cancer risk. NIOSH has also expressed risk as lifetime excess risk per 1,000 miners, an expression that can easily be interpreted by both experts and lay persons.
- NIOSH has used all currently available information and the most extensive pertinent set of human data to estimate risk. The USPHS study of uranium miners [Lundin et al. 1971] is the most extensive set of data available in the United States on the radon progeny exposure of underground miners. Unlike other analyses, this study used the entire qualifying cohort in the risk assessment, regardless of exposure level. These investigators felt this was the most valid way to analyze epidemiologic data using the selected model.

- NIOSH has considered alternative recommendations for risk control that are based on viable exposure limits and engineering controls. The considered options ranged from proposing no REL to prohibiting all occupational exposure to radon progeny. The REL presented in this document was chosen after a thorough weighing of the available data and Institute mandates.
- NIOSH has advanced the process of risk assessment and policy development by conducting the most thorough risk assessment possible on underground miners exposed to radon progeny. The NIOSH risk assessment permitted estimation of lung cancer risk at the lower range of the observed exposure levels. The assessment also suggested meaningful research areas such as lung cancer risks at low radon exposure levels, synergistic effects of other exposures such as cigarette smoke, effects of radon progeny on late versus early stage cancer, and the need for improved engineering control of exposure.

An extensive and complicated process has been used to develop the recommendations in this criteria document. After weighing the conclusions drawn from available data, the mandates of the Institute, and the public health issues, NIOSH recommends an annual cumulative exposure limit of no more than 1 WLM per year. However, as stated earlier, even this exposure poses a significant risk of lung cancer over a working lifetime. Thus NIOSH further recommends that mine operators regard this REL as an upper limit and that they make every effort to limit radon progeny to the lowest possible concentrations. In addition, NIOSH wishes to emphasize the fact that this standard contains many important provisions in addition to the annual exposure limit. These include recommendations for limited work shift concentrations of radon progeny, sampling and analytical methods, recordkeeping, medical surveillance, posting of hazardous information, respiratory protection, worker education and notification, and sanitation. All of these recommendations help minimize risk.

NIOSH recognizes its commitment to protect the health of the Nation's miners and will continue to reexamine this complex occupational health issue. Research on new and more effective methods for reducing occupational exposures will improve the available control technologies. Additional data on exposure levels and associated health risks will permit firmer estimates of risk and hence better recommendations. NIOSH will revise its recommended standard as important new data become available.

REFERENCES

- AIF [1984]. Exposure of U.S. underground uranium miners to radon daughters in 1982 as reported by 29 underground uranium mine operations, from a survey made April 24, 1984. Unpublished report submitted to Mine Safety and Health Administration by Atomic Industrial Forum.
- AIF [1986]. Exposure of U.S. underground uranium miners to radon daughters in 1984 as reported by 20 underground uranium mine operations, from a survey made December 11, 1986. Unpublished report submitted to Mine Safety and Health Administration by Atomic Industrial Forum.
- Auxier JA, Becker K, Robinson EM, Johnson DR, Boyett RH, Abner CH [1971]. A new radon progeny personal dosimeter. *Health Phys* 21:126.
- Axelsson O, Sundell L [1978]. Mining, lung cancer and smoking. *Scand J Work Environ Health* 4:46-52.
- BLS [1987]. Occupational injuries and illnesses in the United States by industry, 1985. Washington, DC: U.S. Department of Labor, Bureau of Labor Statistics, Bulletin No. 2270.
- Bernhard S, Pineau JF, Rannou A, Zettwoog P [1984]. 1983: One year of individual dosimetry in French mines. In: Stocker H, ed. Proceedings of the International Conference on Occupational Radiation Safety in Mining. Volume 1. Toronto, Ontario, Canada: Canadian Nuclear Association, pp. 526-540.
- Bigu J, Kaldenbach R [1984]. Theory, operation and performance of a time-integrating, continuous, radon (thoron) daughter working level monitor. *Radiat Prot Dosimetry* 9:19-26.
- Bigu J, Kaldenbach R [1985]. A microprocessor based continuous monitor with alpha spectroscopy capabilities for the determination of radon, thoron and their progeny. *Radiat Prot Dosimetry* 12:251-260.
- Bloomster CH, Enderlin WI, Young JK, Dirks JA [1984a]. Cost survey for radon daughter control by ventilation and other control techniques. Volume I. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152932.
- Bloomster CH, Jackson PO, Dirks JA, Reis JW [1984b]. Cost survey for radon daughter control by ventilation and other control techniques: radon emissions from underground uranium mines. Volume II. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152940.
- Borak TB, Franco E, Schiager KJ, Johnson JA, Holub HF [1981]. Evaluation of recent developments in radon progeny measurements. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 419-425.

Boyd JT, Doll R, Faulds JS, Leiper J [1970]. Cancer of the lung in iron ore (haematite) miners. *Br J Ind Med* 27:97-105.

Breslin AJ, George AC, Weinstein MS [1969]. Investigation of the radiological characteristics of uranium mine atmospheres. New York, NY: Atomic Energy Commission, New York Operations Office, Health and Safety Laboratory. HASL-220, December 1969.

Brookins DG [1986]. Indoor and soil Rn measurements in the Albuquerque, New Mexico, area. *Health Phys* 51:529-533.

Casarett AP [1968]. Radiation biology. Englewood Cliffs, NJ: Prentice-Hall, Inc.

CCERP [1985]. Risk assessment and risk management of toxic substances. A report to the Secretary, Department of Health and Human Services (DHHS). DHHS Committee to Coordinate Environmental and Related Programs.

CFR. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Chameaud J, Perraud R, Lafuma J, Masse R, Pradel J [1974]. Lesions and lung cancers induced in rats by inhaled radon 222 at various equilibriums with radon daughters. In: Karbe E, Park JF, eds. Experimental lung cancer: carcinogenesis and bioassays. New York, NY: Springer Verlag, pp. 411-421.

Chameaud J, Perraud R, Chretien J, Masse R, Lafuma J [1980]. Combined effects of inhalation of radon daughter products and tobacco smoke. In: Sanders CL, Cross FT, Dagle GE, Mahaffey JA, eds. Proceedings of the Nineteenth Annual Hanford Life Sciences Symposium on Pulmonary Toxicology of Respirable Particles. U.S. Department of Energy, Technical Information Center. NTIS CONF-791002, pp. 551-557.

Chameaud J, Perraud R, Masse R, Lafuma J [1981]. Contribution of animal experimentation to the interpretation of human epidemiological data. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 222-227.

Chameaud J, Perraud R, Chretien J, Masse R, Lafuma J [1982]. Lung carcinogenesis during in vivo cigarette smoking and radon daughter exposure in rats. *Recent Results Cancer Res* 82:11-20.

Chameaud J, Masse R, Lafuma J [1984a]. Influence of radon daughter exposure at low doses on occurrence of lung cancer in rats. *Radiat Prot Dosimetry* 7:385-388.

Chameaud J, Masse R, Morin M, Lafuma J [1984b]. Lung cancer induction by radon daughters in rats. In: Stocker H, ed. Proceedings of the International Conference on Occupational Radiation Safety in Mining. Volume 1. Toronto, Ontario, Canada: Canadian Nuclear Association, pp. 350-353.

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

Corkill DA, Dory AB [1984]. A retrospective study of radon daughter concentrations in the workplace in the fluorspar mines of St. Lawrence, NFLD. Ottawa, Canada: Atomic Energy Control Board, July 1984, INFO-0127.

Cross FT [1984]. A review of radon inhalation studies in animals with reference to epidemiological data. In: Assessment of the scientific basis for existing federal limitations on radiation exposure to underground uranium miners. Unpublished report prepared for the American Mining Congress by Senes Consultant Ltd. Appendix C, pp. 1-66.

Cross FT, Palmer RF, Busch RH, Filipy RE, Stuart BO [1981]. Development of lesions in Syrian Golden Hamsters following exposure to radon daughters and uranium ore dust. Health Phys 41:135-153.

Cross FT, Palmer RF, Filipy RE, Dagle GE, Stuart BO [1982a]. Carcinogenic effects of radon daughters, uranium ore dust and cigarette smoke in beagle dogs. Health Phys 42(1):33-52.

Cross FT, Palmer RF, Dagle GE, Busch RH, Buschbom RL [1982b]. Influence of radon daughter exposure rate, unattachment fraction, and disequilibrium on occurrence of lung tumours. Radiat Prot Dosimetry 7(1-4):381-384.

Cross FT, Buschbom RL, Dagle GE, et al. [1983]. Inhalation hazards to uranium miners. In: Drucker H, et al., eds. Pacific Northwest Laboratory annual report for 1982 to the DOE Office of Energy Research - Part 1, biomedical sciences. Richland, WA: Pacific Northwest Laboratory, pp. 77-80, DE83 007585.

Cross FT, Buschbom RL, Dagle GE, et al. [1984]. Inhalation hazards to uranium miners. In: Park JF, et al., ed. Pacific Northwest Laboratory Annual Report for 1983 to the DOE Office of Energy Research - Part 1, Biomedical Sciences. Richland, WA: Pacific Northwest Laboratory, pp. 41-44, DE84 007437.

Damber L, Larsson L-G [1982]. Combined effects of mining and smoking in the causation of lung carcinoma: A case-control study in northern Sweden. Acta Radiol (Oncol) 21:305-313.

Domanski T, Chruscielewski W, Swiatnicki G [1982]. The performance of passive differentiating track detectors containing a diffusion barrier. Radiat Prot Dosimetry 2:27-32.

Doull J, Klaassen CD, Amdur MO [1980]. Casarett and Doull's toxicology: the basic science of poisons. Second edition. New York, NY: Macmillan Publishing Co., Inc.

Drouillard RF, Holub RF [1977]. Continuous working-level measurements using alpha or beta detectors. Denver, CO: U.S. Department of the Interior, Bureau of Mines. Report of Investigation RI-8237.

Drouillard RF, Holub RF [1985]. Continuous radiation working-level detectors. Denver, CO: U.S. Department of the Interior, Bureau of Mines. Information Circular IC-9029.

Durkin J [1977]. An electronic instrument for radon daughter dosimetry. Denver, CO: U.S. Department of the Interior, Bureau of Mines. Investigation Report 8255.

Edling C, Axelson O [1983]. Quantitative aspects of radon daughter exposure and lung cancer in underground miners. *Br J Ind Med* 40:182-187.

EPA, CDC [1986]. A citizen's guide to radon. U.S. Environmental Protection Agency and U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, August 1986. OPA-86-004.

Evans RD [1969]. Engineers' guide to the elementary behavior of radon daughters. *Health Phys* 17:229-252.

Federal Register [1986]. 30 CFR 45678-45688, Part 57, December 19, Mine Safety and Health Administration. Ionizing radiation standards for underground metal and nonmetal mines. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Filipy RE, Dagle GE, Palmer RF, et al. [1977a]. Carcinogenesis of inhaled radon daughters with uranium ore dust in beagle dogs. In: Thompson RC et al., eds. Pacific Northwest Laboratory annual report for 1976 to the ERDA Assistant Administrator for Environment and Safety. Richland, WA: Battelle Laboratories, pp. 49-52.

Filipy RE, Palmer RF, Stuart BO [1977b]. Non-neoplastic pulmonary disease from inhaled radon daughters with uranium ore dust in beagle dogs. In: Thompson RC, et al., ed. Pacific Northwest Laboratory Annual Report for 1976 to the ERDA Assistant Administrator for Environment and Safety. Richland, WA: Battelle Laboratories, BNWL-2100 PT1, pp. 52-55.

Fox AJ, Goldblatt P, Kinlen LJ [1981]. A study of the mortality of Cornish tin miners. *Br J Ind Med* 38:378-380.

Gaven JC, Palmer RF, McDonald KE, Lund JE, Stuart BO [1977]. Comparative toxicity in rats vs. hamsters of inhaled radon daughters with and without uranium ore dust. In: Thompson RC, et al., eds. Pacific Northwest Laboratory Annual Report for 1976 to the ERDA Assistant Administrator for Environment and Safety. Richland, WA: Battelle Laboratories, BNWL-2100 PT1, pp. 56-60.

Grealy G, Peggie J, Leads V, Solomon S [1982]. A radon and thoron integrating personal dosimeter. *Radiat Prot Dosimetry* 1:207.

Haider B, Jacobi W [1973]. Long-term measurements of radon daughter activity in mines. In: Proceedings of the 3rd International Conference of the International Radiation Protection Association. Washington, DC: U.S. Atomic Energy Commission, p. 920.

Holaday DA, Rushing DE, Coleman RD, Woolrich PF, Kusnetz HL, Bale WF [1957]. Control of radon and daughters in uranium mines and calculations on biologic effects. Washington, DC: U.S. Department of Health, Education, and Welfare, Public Health Service, Bureau of State Services, Division of Special Health Services, Occupational Health Program. Public Health Service Publication No. 494.

Holmgren RM [1974]. Working levels of radon daughters in air determined from measurements of RaB + RaC. *Health Phys* 27:141.

Holub RF [1980]. Evaluation and modification of working level measurement methods. *Health Phys* 39:425.

Howe GR, Nair RC, Newcombe HB, Miller AB, Abbatt JD [1986]. Lung cancer mortality (1950-80) in relation to radon daughter exposure in a cohort of workers at the Eldorado Beaverlodge Uranium Mine. *JNCI* 77:357-362.

ICRP [1977]. Annals of the International Commission on Radiological Protection: Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. New York, NY: Pergamon Press.

ICRP [1981]. Annals of the International Commission on Radiological Protection: Limits for inhalation of radon daughters by workers. ICRP Publication 32. New York, NY: Pergamon Press.

James AC, Strong JD [1973]. A radon daughter monitor for use in mines. In: Proceedings of the 3rd International Conference of the International Radiation Protection Association. Washington, DC: U.S. Atomic Energy Commission, p. 932.

Jingyuan Z, Xiehua W, Xinhui H, et al. [1981]. Investigation of the radioactive etiological factors of lung cancer among miners. *Zhongguo Yixue Kexueyuan Xuebao* 3:127-131 (in Chinese).

Jorgensen HS [1973]. A study of mortality from lung cancer among [iron ore] miners in Kituna 1950-1970. *Work Environ Health* 10:126-133.

Jorgensen HS [1984]. Lung cancer among underground workers in the iron ore mine of Kiruna based on thirty years of observation. *Ann Acad Med, Singapore* 13:371-377.

Kalos F [1986]. Study factors that influence the use of respirators in uranium mines. Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, INFO-0193. A report prepared for the Atomic Energy Control Board, Ottawa, Canada.

Kawaji M, Pai HL, Phillips CR [1981]. Use of gross filter activities in a continuous working level monitor. *Health Phys* 40:543-548.

- Kunz E, Sevc J, Placek V [1978]. Lung cancer mortality in uranium miners (methodological aspects). *Health Phys* 35:579-580.
- Kusnetz HL [1956]. Radon daughters in mine atmospheres, a field method for determining concentrations. *Am Ind Hyg Assoc Q* 17:87.
- Linauskas SH, Kalos F [1984]. Study of efficiency and current use of respiratory protective devices. Atomic Energy of Canada Limited, INFO-0144. A report prepared for the Atomic Energy Control Board, Ottawa, Canada.
- Lundin FE, Wagoner JK, Archer VE [1971]. Radon daughter exposure and respiratory cancer: quantitative and temporal aspects. U.S. Department of Health, Education, and Welfare, Public Health Service, National Institute for Occupational Safety and Health, National Institute of Environmental Health Sciences, Joint Monograph No. 1.
- MMWR [1987]. National traumatic occupational fatalities. *Morbidity and Mortality Weekly Report* 36(28):461-464.
- McCurdy DE, Schiager KJ, Flack ED [1969]. Thermoluminescent dosimetry for personal monitoring of uranium miners. *Health Phys* 17:415.
- Monson RR [1980]. Occupational epidemiology. Boca Raton, FL: CRC Press, Inc., 219 pp.
- Morrison HI, Semenciw RM, Mao Y, et al. [1985]. Lung cancer mortality and radiation exposure among the Newfoundland fluorspar miners. In: Stocker H, ed. Proceedings of the International Conference on Occupational Radiation Safety in Mining. Volume 1. Toronto, Ontario, Canada: Canadian Nuclear Association, pp. 365-368.
- MSHA [1986]. Preliminary regulatory cost analysis and regulatory flexibility statement - ionizing radiation standards for underground metal and nonmetal mines, 30 CFR part 57. Unpublished report released to the National Institute for Occupational Safety and Health by the Mine Safety and Health Administration, Arlington, VA, December 1, 1986.
- Muller J, Wheeler WC, Gentleman JF, Suranyi G, Kusiak R [1985]. Study of mortality of Ontario miners. In: Stocker H, ed. Proceedings of the International Conference on Occupational Radiation Safety in Mining. Volume 1. Toronto, Ontario, Canada: Canadian Nuclear Association, pp. 335-343.
- NAS [1987]. The effects on populations of exposure to low levels of ionizing radiation. Washington, DC: National Academy of Sciences (NAS) Committee on the Biological Effects of Ionizing Radiations (BIER), National Academy Press.
- National Safety Council [1981]. Falls on floors. Chicago, IL: National Safety Council, Data Sheet 1-495-81.

NCRP [1975]. Natural background radiation in the United States. Bethesda, MD: National Council on Radiation Protection and Measurements Report No. 45.

NCRP [1984a]. Exposures from the uranium series with emphasis on radon and its daughters. Bethesda, MD: National Council on Radiation Protection and Measurements Report No. 77.

NCRP [1984b]. Evaluation of occupational and environmental exposures to radon and radon daughters in the United States. Bethesda, MD: National Council on Radiation Protection and Measurements Report No. 78.

NIOSH [1975a]. Criteria for a recommended standard: occupational exposure to inorganic arsenic. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 75-149.

NIOSH [1975b]. Criteria for a recommended standard: occupational exposure to chromium(VI). Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 76-129.

NIOSH [1977]. Criteria for a recommended standard: occupational exposure to inorganic nickel. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 77-164.

NIOSH [1985]. Evaluation of epidemiologic studies examining the lung cancer mortality of underground miners. Unpublished report submitted to the Mine Safety and Health Administration, May 9, 1985. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer.

NIOSH [1987]. NIOSH respirator decision logic. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer. DHHS (NIOSH) Publication No. 87-108.

NTP [1984]. National Toxicology Program--Technical Report Series No. 248. Toxicology and carcinogenesis studies of 1,3-butadiene (CAS No. 106-99-0) in B6C3F₁ mice (Inhalation Studies). U.S. Department of Health and Human Services, Public Health Service, National Institutes of Health, NIH Publication No. 84-2544:2.

Pham QT, Gaertner M, Mur JM, et al. [1983]. Incidence of lung cancer among iron miners. *Eur J Respir Dis* 64:534-540.

Phillips CR, Pai HL, Jokura K [1979]. Comparative evaluation of CEA track etch and LiF TLD personal alpha dosimeters of radon and thorium in a uranium mine. Ottawa, Ontario, Canada: Atomic Energy Control Board, AECB-1170.

Placek V, Smid A, Sevc J, Tomasek L, Vernerova P [1983]. Late effects at high and very low exposure levels of the radon daughters. In: Broerse JJ, Barendsen GW, Kal HB, Vanderkogel AJ, eds. Radiation research - somatic and genetic effects. Proceedings of the Seventh International Congress of Radiation Research, Amsterdam, the Netherlands, July 3-8, 1983.

PNL [1978]. Study of the combined effects of smoking and inhalation of uranium ore dust, radon daughters and diesel oil exhaust fumes in hamsters and dogs. Richland, WA: Pacific Northwest Laboratory, PNL-2744.

Radford EP, Renard KGSC [1984]. Lung cancer in Swedish iron miners exposed to low doses of radon daughters. *N Engl J Med* 310:1485-1494.

Radiation Policy Council [1980]. Report of the task force on radon in structures. Washington, D.C.: The Council, RPC-80-002.

Rolle R [1972]. Rapid working level monitoring. *Health Phys* 22:233.

Samet JM, Kutvirt DM, Waxweiler RJ, Key CR [1984]. Uranium mining and lung cancer in Navajo men. *N Engl J Med* 310:1481-1484.

Schiager KJ [1977]. The 3R-WL working level survey meter. *Health Phys* 33:595-604.

Schiager KJ, Borak TB, Johnson JA [1981]. Radiation monitoring for uranium miners: evaluation and optimization. Fort Collins, CO: U.S. Department of Interior, Bureau of Mines.

Sevc J, Kunz E, Placek V [1976]. Lung cancer in uranium mines and long-term exposure to radon daughter products. *Health Phys* 30:433-437.

Sevc J, Kunz E, Placek V, Smid A [1984]. Comments on lung cancer risk estimates. *Health Phys* 46:961-964.

Shapiro J [1981]. Radiation protection--A guide for scientists and physicians. 2nd edition. Cambridge, MA: Harvard University Press.

Sheeran CT, Franklin JC [1984]. Microcomputer-based monitoring and control system with uranium mining application. Spokane, WA: U.S. Department of the Interior, Bureau of Mines. Information Circular IC-8981.

Shreve JD [1976]. Presentation at Specialist Meeting on Personal Dosimetry and Area Monitoring Suitable for Radon and Radon Daughter Products. Elliott Lake, Ontario, Canada.

Shreve JD, Miller RW, Cleveland JE [1977]. A new instrument for quick determination of radon and radon daughter concentrations in air - concept, analytical basis, calibration caveats: The embodiment and field results. In: Proceedings of the 4th International Conference of the International Radiation Protection Association. Washington, DC: U.S. Atomic Energy Commission, p. 111.

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

Solli HM, Andersen A, Strandén E, Langard S [1985]. Cancer incidence among workers exposed to radon and thoron daughters at a niobium mine. Scand J Work Environ Health 11:7-13.

Southwest Research Institute [1980]. Radon daughter dosimeter tests in active uranium mines. San Antonio, TX: Southwest Research Institute.

Stevens GA, Moyer ES [1987]. Efficiency dependence of commercial respirator filters on humidity pretreatment. Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Safety Research.

Szymusiak SM, Ryan JP [1982a]. Prevention of slip and fall injuries, Part I. Professional Safety, June, pp. 11-15.

Szymusiak SM, Ryan JP [1982b]. Prevention of slip and fall injuries, Part II. Professional Safety, July, pp. 30-35.

Tirmarche M, Brenot J, Piechowski J, Chameaud J, Pradel J [1985]. The present state of an epidemiological study of uranium miners in France. In: Stocker H, ed. Proceedings of the International Conference on Occupational Radiation Safety in Mining. Volume 1. Toronto, Ontario, Canada: Canadian Nuclear Association, pp. 344-349.

Tsivoglou EC, Ayer HE, Holaday DA [1953]. Occurrence of nonequilibrium atmosphere mixtures of radon and its daughters. Nucleonics 11:40.

Urban M, Binns DAC, Estrada JJ [1985]. Radon measurements in mines and dwellings. Kernforschungszentrum Karlsruhe GmbH, Report No. KfK 3866, CNEN 1101. Available from NTIS.

Wagoner JK, Miller RW, Lundin FE, Fraumeni JF Jr., Haij ME [1963]. Unusual cancer mortality among a group of underground metal miners. N Eng J Med 269:284-289.

Wang CH, Willis DL, Loveland WD [1975]. Radiotracer methodology in the biological, environmental, and physical sciences. Englewood Cliffs, NJ: Prentice-Hall, Inc.

- Wang X, Huang X, Huang S, et al. (1984). Radon and miners lung cancer. *Zhonghua Fangshe Yixue Fanghu Zazhi* 4:10-14 (in Chinese).
- Waxweiler RJ, Roscoe RJ, Archer VE, Thun MJ, Wagoner JK, Lundin FE [1981]. Mortality follow-up through 1977 of the white underground uranium miners cohort examined by the United States Public Health Service. In: Gomez M, ed. *International Conference: Radiation Hazards in Mining*. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 823-830.
- White O [1971]. Evaluation of MOD and ORNL radon daughter dosimeters. Washington, DC: U.S. Atomic Energy Commission, Health and Safety Laboratory Technical Memorandum 71-17.
- White MK, Ronk R [1984a]. Do you have a hot and/or strenuous job? *Professional Safety*, May, pp. 27-29.
- White MK, Ronk R [1984b]. Chemical protective clothing and heat stress. *Professional Safety*, December, pp. 34-38.
- White MK, Hodous TK [1987]. Reduced work tolerance associated with wearing protective clothing and respirators. *Am Ind Hyg Assoc J* 48(4):304-310.
- White MK, Hodous TK, Hudnall JB [1987]. Physiological and subjective responses to working in disposable protective coveralls and respirators commonly used by the asbestos abatement industry (draft report). Morgantown, WV: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.
- Whittemore AS, McMillan A [1983]. Lung cancer mortality among U.S. uranium miners: A reappraisal. *JNCI* 71(3):489-499.
- WHO [1979]. World Health Organization. IARC monographs on the evaluation of the carcinogenic risk of chemicals to humans. Polynuclear aromatic compounds, part 3, industrial exposures in aluminum production, coal gasification, coke production, and iron and steel founding. IARC Monographs, Vol 34; supplement 1.
- Zettwoog PR [1981]. State-of-the-art of individual dosimetry in France. In: Gomez M, ed. *International Conference: Radiation Hazards in Mining*. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., pp. 321-331.

APPENDICES

APPENDIX I

**EVALUATION OF EPIDEMIOLOGIC STUDIES EXAMINING
THE LUNG CANCER MORTALITY OF UNDERGROUND MINERS**

Report Prepared for the
U.S. Mine Safety and Health Administration

by

Division of Standards Development and Technology Transfer
National Institute for Occupational Safety and Health (NIOSH)
Centers for Disease Control
Cincinnati, Ohio 45226

May 9, 1985

CONTENTS

- I. Summary
- II. Introduction
- III. Evaluation of Epidemiologic Evidence
 - A. Introduction
 - B. Uranium Miners in the United States
 - C. Uranium Miners in Czechoslovakia
 - D. Uranium Miners in Ontario
 - E. Iron Miners in Sweden
 - F. Fluorspar Miners in Newfoundland
 - G. Secondary Epidemiologic Studies
 - H. Smoking
 - I. Discussion and Conclusions Related to the Epidemiologic Evaluation
- IV. Medical Screening and Surveillance of Underground Miners Exposed to Short-Lived Alpha Particles
- V. Technical Feasibility of Lowering the Standard
- VI. Conclusion
- VII. References
- VIII. Appendices
 - A. Mining Industry: Current Workforce and Typical Radiation Exposure
 - B. Current Methods of Control of Radiation Exposures in Underground Mines
- IX. Glossary

I. SUMMARY

The National Institute for Occupational Safety and Health (NIOSH) submits this report in response to the Mine Safety and Health Administration's (MSHA) Advanced Notice of Proposed Rulemaking (ANPR) concerning radiation standards for metal and nonmetal mines. In fifteen epidemiologic studies, researchers reported excess lung cancer deaths among underground miners who worked in mines where radon progeny were present. In addition, several studies show a dose-response relationship between radon progeny exposure and lung cancer mortality. In two recent studies, investigators report excess lung cancer deaths due to mean cumulative radon progeny exposures below 100 Working Level Months (WLM) (specifically, at 40-90 WLM and 80 WLM).

The health risks from other exposures (i.e., arsenic, diesel exhaust, smoking, chromium, nickel, and radiation) in the mining environment can affect lung cancer risks due to radon progeny exposure. Unfortunately, the literature contains limited information about other exposures found in mines. The available information, concerning whether cigarette smoke and radon progeny exposures act together in an additive or multiplicative fashion is inconclusive; nevertheless, a combined exposure to radon progeny and cigarette smoke results in a higher risk than exposure to either one alone.

X-ray surveillance and sputum cytology appear to be ineffective in the prevention of radon progeny-induced lung cancers in individual miners; therefore, these techniques are not recommended. Also, at this point, there is insufficient evidence to conclude that there is an association between one specific lung cancer cell type and radon progeny exposure.

According to annual radon progeny exposure records from the Atomic Industrial Forum (AIF) and MSHA, it is technically feasible for the United States mining industry to meet a standard lower than the current annual exposure limit of 4 WLM. Recent engineering research suggests that it is technically feasible for mines to meet a standard as low as 1 WLM. Based upon qualitative analysis of these studies and public health policy, NIOSH recommends that the annual radon progeny permissible exposure limit (PEL) of 4 WLM be lowered. NIOSH wishes to withhold a recommendation for a specific PEL, until completion of a NIOSH quantitative risk assessment, which is now in progress.

II. INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) submits this report in response to the Mine Safety and Health Administration's (MSHA) Advanced Notice of Proposed Rulemaking (ANPR) concerning radiation standards for metal and nonmetal mines. This report evaluates fifteen epidemiologic studies that examine the lung cancer mortality of underground miners exposed to radon progeny. The fifteen studies are divided into two groups: five primary studies and ten secondary studies. Overall, the ten secondary studies provide additional information about the association between lung cancer mortality and radon progeny exposure, yet have more limitations (in study design, study population size, radon exposure records, thoroughness of follow-up, etc.) than the five primary studies. Recommendations for the medical surveillance of underground miners exposed to radon progeny are included. The United States mining industry's ability to meet a radon progeny exposure standard lower than the present four Working Level Months (WLM), based solely on technical feasibility, is also discussed.

A working level (WL) is a standard measure of the alpha radiation energy in air. This energy can result from the radioactive decay of radon (Rn-222) and thoron (Rn-220) gases. A WL is defined as any combination of short-lived radon decay products (polonium-218, lead-214, bismuth-214, polonium-214) per liter of air that will result in the emission of 1.3×10^5 million electron volts (MeV) of alpha energy [1]. NIOSH defines a WLM as an exposure to 1 WL for 170 hours.

For the information of the reader, two appendices and a glossary are included. Appendix A contains data from the Atomic Industrial Forum (AIF) an organization representing the interests of the United States uranium mining industry, and MSHA on the numbers and radon progeny exposures of underground miners in the United States. Appendix B lists methods currently in use for controlling radon progeny exposures underground. Finally, there is a glossary containing epidemiologic and health physics terms.

III. EVALUATION OF EPIDEMIOLOGIC EVIDENCE

A. Introduction

This report examines five primary and ten secondary epidemiologic studies of underground miners. It describes the important points, strengths, and limitations of each study. The five primary epidemiologic studies examined lung cancer mortality among uranium miners in the United States, Czechoslovakia, and Ontario; iron miners in Malmberget, Sweden; and fluorspar miners in Newfoundland. The ten secondary epidemiologic studies examined mortality among iron ore miners in Grangesberg, Gallivare, and Kiruna, Sweden; zinc-lead miners in Sweden; metal and Navajo uranium miners in the United States; tin and iron ore miners in Great Britain; uranium miners in France; and tin miners in Yunnan, China. Finally, two recent studies analyze the interaction between radon progeny exposure and smoking.

This report focuses on the lung cancer experience of these fifteen underground mining cohorts. In general, the study cohorts did not show excess mortality due to cancers other than lung, except for four studies that reported excess stomach cancers and one report of excess skin cancer among underground miners. Excess stomach cancers were reported among underground tin miners in Cornwall, England (standardized mortality ratio (SMR) = 200, p value unspecified by the authors, however estimated at $p < 0.05$, from the observed deaths and the Poisson frequency distribution) [2]; gold miners in Ontario (SMR=148, $p < 0.001$) [3]; metal miners in the United States (SMR=149, $p < 0.01$) [4]; and iron ore miners in Sweden (SMR=189, $p < 0.01$) [5]. Sevcova et al. (1978) [6] reported excess skin cancers among underground uranium miners in Czechoslovakia (an observed skin cancer incidence of 28.6 versus an expected of 6.3 per 10,000 workers; $p < 0.05$), that they attributed to external alpha radiation from radon progeny. Arsenic is present in the Czechoslovakian uranium mines (arsenic levels unidentified) [7] and the association between arsenic and skin cancer is well documented [8,9]. The excess mortality from stomach and skin cancers among these cohorts needs further study.

In all five primary epidemiologic studies, the exposure records for the individual miners lack precision. Frequently, an individual miner's exposure was calculated from an annual average radon progeny exposure estimate for a particular mine or mine area, thus, an individual miner's true exposure could vary greatly from the estimated exposure. Of the five primary epidemiologic studies, the Czechoslovakian study has the best records for radon progeny exposure [10]. The Swedish study has limited exposure records for their cohort (8 years of measurements for 44 years of follow-up), and the miners' mean exposures were about five WLM per year [5]. The lower radon progeny concentrations found in Swedish mines indicate that the potential error due to excursions in concentration was less than in mines in the United States, Newfoundland, and Ontario, where higher concentrations were measured (Table III-2). Overall, the radon progeny exposure records from the United States, Ontario, and Newfoundland have similar limitations (detailed in sections B, D, and F). WL measurements made in uranium mines in the United States and fluorspar mines in Newfoundland fluctuated greatly, reaching unusually high radon progeny

concentrations: in the fluorspar mines, a maximum of 200 WL [11], and in the uranium mines, 3 out of 1,700 mines averaged over 200 WL [12]. NIOSH is currently investigating the variability and quality of the exposure records kept for uranium mines in the United States. Exposure data quality, although important, does not solely determine a study's strength; one should also evaluate the epidemiologic and statistical methods used.

This review reports both the attributable and relative risk estimates for lung cancer (see Glossary for definitions) when they are provided by the authors [3,5,13,14].

B. Uranium Miners in the United States

1. Description

The United States Public Health Services (USPHS) conducted an epidemiologic study examining mortality among underground uranium miners from the Colorado Plateau [12,15]. Beginning in July 1950, USPHS researchers medically examined 3,362 white and about 780 nonwhite males who had worked at least 1 month underground in uranium mines as of January 1, 1964 [15]. Lundin et al. (1971) [12] reported on mortality among both white and nonwhite miners, whereas a subsequent follow-up by Waxweiler et al. (1981) [15] focused on the white male subcohort. In addition, Samet et al. (1984) conducted a case-control study using some miners from the nonwhite male subcohort [16] (see Secondary Epidemiologic Studies).

The USPHS cohort was followed through December 31, 1977, with a mean follow-up of 19 years; their mean cumulative radon progeny exposure was 821 WLM (median of 430 WLM) [15]. The exposure data is skewed towards high exposures; the large difference between the mean and median (821 vs 430), signifies that a small number of miners received very high exposures.

Job turnover in the uranium mines was substantial; the majority of miners worked less than 10 years underground (not accounting for gaps in employment) [14]. Nevertheless, approximately 33 percent of the cohort worked 10 or more years and 7 percent worked 20 or more years underground in uranium mines (not accounting for gaps in employment) [15]. The number of months worked underground ranged from 1 to 370 (over 30 years), with a median of 48 months (4 years).

Some miners worked underground in uranium or nonuranium mines before they entered the USPHS study, and before radon progeny levels were recorded. Among these miners, 13.7 percent started mining before 1947 [15]. The cohort's early radon progeny exposures probably represented a small proportion of their total lifetime exposures; Lundin et al. (1971) noted that the study group accumulated only 16 percent of their total radon progeny exposure before 1950 [12].

A bias toward overestimating exposure and a narrow sampling strategy were two major influences effecting the miners' exposure records. First, some of the USPHS exposure data records were biased by including

disproportionately more measurements from mine areas with high radon progeny levels. Radon progeny samples taken during 1951-1960 were stated to be representative of the mine areas in which miners received exposures. Also, the U.S. Bureau of Mines (USBOM), the New Mexico State Health Department, and the Arizona mine inspector continued to take representative samples after 1960 [12]. During 1960-68, however, additional radon progeny samples were collected for control purposes by mine inspectors from Colorado, Utah, and Wyoming [12]. In this case, inspectors sampled disproportionately more mines and mine sections that had high radon progeny levels. This sampling bias also tended to increase estimates for geographic areas of mining (locality, district, or state) [12]. Thus, some average annual WL exposure records collected during 1960-68 overestimated the uranium miners' exposure.

Second, there is little exposure data available for some uranium mines, especially small mines. For the entire period 1951-68, nearly 43,000 measurements were available to characterize about 2,500 uranium mines. More samples were usually taken in the larger mines that employed most of the miners. In many mines, however, only one or two samples were ever taken [12].

At the present time, the USPHS exposure data set has 34,120 "average" (undefined by Lundin et al. 1971) annual WL exposure records from 1,706 surface and underground uranium mines, made over a 20-year period (1951-1971) [12,17]. These records consist of "guesstimates", "estimates", "extrapolations", and actual WL measurements (Table III-1). Based on a preliminary analysis of these four types of exposure records, NIOSH concludes that cumulative exposure estimates based on extrapolated and estimated WL values (probably guesstimates as well) were nearly as accurate as those based solely on measured WL values. As part of the quantitative risk assessment in preparation, NIOSH will further analyze precision and accuracy in the exposure records.

Lundin et al. (1971) assigned one "average" annual WL value to a mine for a given year. Only 10 percent of these annual WL values were based on actual measurements made in surface and underground uranium mines (Table III-1). To estimate an individual miner's cumulative exposure, one must record the WL present in the mine, and the time the miner worked underground. The researchers based their work history information on interviews with the miners, an annual census, annual questionnaires, and the Colorado Mine Inspectors Census [12].

Among the white male cohort, 185 lung cancer deaths have been observed, compared with 38.4 expected, giving a SMR of 482 ($p < 0.05$) [15]. By the 1977 update, the study of miners in the United States had accumulated 62,556 person years at risk (PYR) (see Appendix A). Waxweiler et al. (1981) used the formula for attributable risk to determine that about 80 percent of the deaths due to lung cancer in this cohort were attributable to uranium mining [15]. As of 1971, statistically significant excess cancers were found in all radon progeny exposure categories above 120 WLM [12]; the exposure categories were: less than 120, 120-359, 360-839, 840-1799, 1800-3719, and 3720 and over, in WLM. NIOSH continues to monitor the mortality experience of this cohort, particularly those workers exposed at or below 120 WLM.

TABLE III-1: RADON PROGENY EXPOSURE DATA SET FOR SURFACE AND UNDERGROUND URANIUM MINES IN THE UNITED STATES*

| Type of Record | Number of Records | Percentage of Total Data Set |
|---------------------------------|-------------------|------------------------------|
| Guesstimate | 1,854 | 5.43 |
| Estimate | 23,159 | 67.88 |
| Extrapolation | 5,602 | 16.42 |
| Measurements | 3,505 | 10.27 |
| Total Average Annual WL Records | 34,120** | 100.00 |

* Based on a recent review of the data set by T. Meinhardt and R. Roscoe (NIOSH) [17].

** There were 32,662 annual average WL estimates for underground uranium mines, 1,458 for surface mines.

"Guesstimates" were annual WL values assigned to mines operating before 1951. Guesstimates were made on the basis of knowledge concerning ore bodies, ventilation practices, emanation rates from different types of ores, and on radon or radon daughter measurements made in 1951 and 1952 [12].

"Estimates" were average WL's for an area based on actual measurements made in a locality, district or state [12].

"Extrapolations" were interpolations or projections of annual WL values based on actual measurements made in the same mine during earlier or later years [12].

The terms "guesstimates," "estimates," and "extrapolations" were defined in this manner by Lundin et al. (1971) [12]; NIOSH recognizes the limitations of these definitions, but uses them for consistency with published reports.

2. Strengths

This is a large, well traced, and analyzed study; the study cohort is clearly defined. It contains smoking histories and radon progeny exposure records for the same individuals. Although the radon progeny exposure data were measured by different persons, a standard sampling and counting technique was used and the technical quality of the measurements was good [12].

3. Limitations

The major limitation in the exposure data quality are that there were few measurements for small mines, (although fewer miners worked in these mines) miners' work histories were self reported, and many exposures

were overestimated during 1960-68 [12]. Another limitation is that many miners fell into high radon progeny exposure categories; however 20 percent of the miners were assigned to the category below 120 WLM [18].

Several reviewers have found that the USPHS study gives lower estimates of risk per WLM for radon progeny exposure than the other four major epidemiologic studies [19,20,21]. This may be due to the overestimation of exposure by Lundin et al. (1971) [12] or other factors.

C. Uranium Miners in Czechoslovakia

1. Description

This cohort consists of 2,433 uranium miners who entered employment between 1948-1952 (Group A) and worked underground at least 4 years [22]. (Sevc, Kunz, and associates plan to report on mortality among a second group of 1,931 uranium miners, (group B), in the future [7]). The miners had moderate exposures to radon progeny, with a mean cumulative exposure of about 289 WLM [23], over an average of 10 years underground (by 1973) [24]. The cohort was followed until the end of 1975, with average follow-up periods of 26 years [25].

Kunz et al. (1978) reported an observed lung cancer rate of 37.2 deaths per 10,000 person years (PY) versus an expected rate of 7.5 deaths per 10,000 PY by 1973. Given these rates and 56,955 total PY, there were 211.8 deaths observed versus 42.7 expected, yielding a SMR of about 496 ($p < 0.05$) [24]. Excess lung cancers were apparent in all radon progeny exposure categories above 100 WLM ($p < 0.05$) [10,24]. The eight exposure categories were: less than 50 WLM, 50-99, 100-149, 150-199, 200-299, 300-399, 400-599, and 600 WLM and over [10].

2. Strengths

One positive feature of this study is the large amount of exposure data available. Radon gas measurements started in 1948, with a minimum mean of 101±8 measurements per mine [10]. Other strengths include the number of workers exposed to low radon progeny levels, a long period of follow-up (average of 26 years by 1975) [24], and the limited exposure to radon progeny from other underground mining (less than 2 percent of the study group members mined nonuranium ores) [10].

In addition, Sevc et al. (1984) investigated the hazards from other exposures, such as silica, arsenic, asbestos, chromium, nickel, and cobalt, and concluded that these were not causing the excess lung cancer risk of the uranium miners [7]. Sevc (1970) reported maximum dust levels between 2.0-10.0 mg/m³ during 1952-56, and stated that the miners' risk of silicosis was relatively low [26]. Chromium, nickel, and cobalt were present only in trace amounts in mine dusts. Although arsenic was present in these mines (concentration unspecified), there was no significant difference in lung cancer mortality between two mining areas with comparable radon progeny exposure levels, but fiftyfold differences in arsenic concentrations [27,28,29,30,31,32].

3. Limitations

The limitations of the Czechoslovakian study are that the exposure estimates made before 1960 were based on radon gas, rather than direct radon progeny measurements. A second limitation is that the cohort definition and the epidemiologic methods used by the Czechoslovakian researchers make it difficult to compare their findings with those from the other four primary studies.

The radon gas and progeny equilibrium ratio is necessary to estimate WL concentrations from radon gas measurements correctly. The authors provided insufficient detail about the equilibrium ratio in the Czechoslovakian uranium mines to allow evaluation of the data quality [10]. If Sevc et al. (1976) had equilibrium ratio records or a reliable way to estimate the equilibrium ratio, then using radon gas exposure measurements to estimate WL would not seriously bias their results.

Sevc, Kunz and associates defined their cohort as men who entered employment in the Czechoslovakian uranium mines in the years 1948-1953 (for Group A miners), and worked underground at least 4 years [22]. It is unclear from the published reports whether the Czechoslovakian miners accumulated their person-years at risk of dying (PYR) from the time they entered the cohort or from their time of first exposure. The cohorts' average 26 years of follow-up by 1975 [25], implies that the PYR were accumulated from a miner's time of first exposure [33]. In most epidemiologic studies, a miner's PYR accumulate after he enters the cohort. The Czechoslovakian method of accumulating PYR makes it difficult to directly compare their lifetable analysis and findings with those from other miner studies. Sevc et al. (1984) also neglected the effect of smoking in their data analysis, although they stated that this would not effect their results, because the percentage of cigarette smokers among miners (70 percent) was comparable to that among the general male population of Czechoslovakia [7].

D. Uranium Miners in Ontario, Canada

1. Description

This is a cohort study of 15,984 uranium miners (excluding those who worked in asbestos mines) who worked at least 1 month underground, and entered the study cohort only after receiving a medical examination between January 1, 1955 and December 31, 1977 [3,34]. Mortality among these miners was followed up to December 31, 1981. Most uranium miners worked for very short periods of time underground (median of 1.5 years), thus resulting in low cumulative exposures to radon progeny (mean of 40-90 WLM) [3].

In Ontario, uranium mining started in 1955, reached a peak in the late 1950's and early 1960's, when an equally fast decline of production and employment set in [3,34]. Most uranium miners, 10,541 out of 15,984 (66 percent) had previous full- or part-time underground mining experience; also, 87 percent of the uranium miners had less than 5 years of uranium mining experience [34]. Depending upon the production needs of

individual mining companies, Ontario miners frequently move from mine to mine and from mining one type of ore to mining another.

The literature has limited information about how radon progeny exposure levels were determined. For the period 1955-1967, Muller et al. (1983) [34] obtained yearly mean radon progeny concentrations for each mine, based on area monitoring, which they called the "Standard Working Level" mine values. Three mining engineers, who were familiar with the Ontario uranium mines during the early years of operation, concluded that the "Standard Working Level" mine values underestimated the miners' true radon progeny exposures. The engineers suggested upper limits for radon progeny concentrations in Ontario mines, which they called the "Special Working Level" mine values. Using the "Standard" and "Special" working level mine values, as well as the miners' work histories, Muller et al. (1983) calculated a range of cumulative radon progeny exposures (in WLM) for each miner, rather than a point estimate. For the period 1968 and later, Muller et al. (1983) obtained area monitoring data for individual miners [34].

As of 1977, among all underground uranium miners, there were 119 lung cancer deaths versus 66 expected, yielding an SMR of 181 ($p < 0.001$). As gold miners who never mined uranium showed an increased lung cancer risk, the uranium miners were split into two groups: uranium miners with no prior gold mining experience and uranium miners with prior gold mining experience. When uranium miners with prior gold mining experience were excluded from the cohort, there were 82 deaths observed versus 57 expected for an SMR of 144 (p value unspecified by authors; however, estimated at $p < 0.05$ from the number of observed deaths and the Poisson frequency distribution). This group of uranium miners (excluding those with prior gold mining experience) accumulated 202,795 PYR; Muller et al. (1985) calculated their attributable risk at 3-7 per 10^6 PY-WLM (with a 10 year lag on exposure) and their excess relative risk at 0.5-1.3 per 100 WLM (see Glossary for definitions). Excess lung cancer deaths occurred at 40-90 WLM [3].

2. Strengths

This study's greatest strength lies in the miners' low mean cumulative exposures (40-90 WLM) to radon progeny, exposures much lower than those reported in the United States, Czechoslovakian, and Newfoundland studies (see Table III-2, at the end of this Chapter). Another good feature of this study is that the researchers carefully traced uranium miners' work experience in other hard rock mines. Large numbers of uranium miners in Ontario (66 percent of the study cohort) had some hard rock mining experience.

3. Limitations

This study has three disadvantages; first, the cohort is severely truncated, with only about 18 years (median value) of follow-up and a median attained age of 39 years by 1977 [34]. A short follow-up on a young cohort creates problems because lung cancer is rarely manifested before age 40 [20,21]. Second, thoron progeny and gamma radiation

levels vary and can reach substantial levels in some Ontario uranium mines [35,36,37]. For example, Cote and Townsend (1981) found that thoron progeny working levels were about half the radon progeny working levels in an Elliot Lake, Ontario uranium mine [37]. The Kusnetz method is frequently used to measure radon progeny in mines and can discriminate between radon and thoron progeny. When used improperly, however, the Kusnetz method can mistakenly count thoron progeny as radon progeny, so that the true radon progeny exposure may be overestimated [37]. From the limited information in the published reports [3,34], it is unclear whether measurement error was introduced by using the Kusnetz method improperly.

There are no epidemiologic data available to estimate the health risks due to thoron progeny. The Advisory Committee on Radiological Protection from the Canadian Atomic Energy Control Board (AECB) reviewed research on microdosimetry which indicated that the main contribution to the WLM from thoron progeny comes from the radioactive decay of long-lived Pb-212 (ThB, the half life=10.6 hours). Its half-life is long enough for the Pb-212 to translocate from the lungs into other tissue, where it emits much of its alpha energy. Radon progeny have shorter half-lives than Pb-212 and emit most of their alpha energy in the lung. Therefore, the AECB concluded that the risk of lung cancer induction by 1 WLM of thoron progeny is about one third of that for 1 WLM of radon progeny [38].

Finally, Muller et al. (1985) published limited information about the smoking habits of these miners, and the researchers' present risk estimates are uncorrected for smoking [3]. Out of a group of 57 uranium miners who died of lung cancer, only one was a nonsmoker and the rest smoked [39]. Muller and associates plan to conduct a case-control study of the effects of smoking upon lung cancer risk in miners. Although they stated that correction for smoking will not substantially change their risk estimates [3], at low levels of radon progeny exposure, it is important to take into account the effect of smoking; thus, definitive conclusions regarding this study must await the smoking history analysis.

E. Iron Miners in Sweden

1. Description

Radford and St. Clair Renard (1984) studied a cohort of 1,294 iron miners, born between 1890 and 1919, who were alive in 1930 and worked underground in more than one calendar year between 1897 and 1976. This cohort received a mean cumulative exposure of 81.4 WLM (the authors lagged dose by five years), at an average rate of 4.8 WLM per year, and by 1976 had been followed up an average of approximately 44 years [5].

Between January 1, 1951 and December 31, 1976, there were 50 lung cancer deaths observed versus 14.6 expected (the authors excluded PY for the first 10 years after start of mining in their calculation of expected deaths) with an SMR of 342 ($p < 0.01$). When expected deaths were adjusted for smoking status, that number decreased to 12.8, with an SMR of 390 (p value unspecified by the authors, however, $p < 0.05$ when estimated from

the observed deaths and the Poisson frequency distribution). This cohort accumulated 26,567 person-years at risk by 1976. Radford and St. Clair Renard (1984), calculated an average attributable risk index of 19 per 10^6 PY-WLM, and an excess relative risk index (see Glossary for definitions) of 3.6 per 10^2 WLM (after adjustment for smoking and latency). There were excess lung cancer deaths at exposures of about 80 WLM ($p < 0.05$, estimated as above) [5].

2. Strengths

The strengths of this study include the relatively low radon progeny exposures of the miners (mean of 4.8 WLM per year), the long follow-up period, and the stability of the work force. The ascertainment of vital status (99.5 percent), and the confirmation of diagnoses for causes of death was thorough (about 50 percent of all deaths in Sweden are followed by autopsy). In addition, Radford and St. Clair Renard (1984) used case-control methods and environmental measurements to rule out health risks from diesel exhaust, iron ore dust, silica, arsenic, chromium, nickel, and asbestos in the mines [5].

3. Limitations

The major limitations of the iron miners' study were the limited exposure data available for analysis and an unclear cohort definition; there was also a question about how the authors adjusted for lung cancer latency. Radon gas, in the Swedish iron mines, was first measured in 1968. That means that for the average 44 years of follow-up, there exist exposure estimates based on actual measurements for only 8 years. The researchers reconstructed past concentrations based on measurements made at each mine level and area during 1968-1972 and on knowledge of the natural and mechanical ventilation used previously. They assumed that mine ventilation systems and radon progeny concentrations during 1968-72 were comparable with those in the past, by analogy with quartz dust levels measured in the mines since the 1930's [5].

The researchers calculated average yearly exposures in WLM for each decade from the average hours per month underground and radon progeny concentrations in each area, weighted by the number of man-hours worked underground [5]. These crude calculations make tenuous the connection between a given individual miner and a particular radon progeny exposure level. Nonetheless, the iron miners as a group, probably received very low average exposures to radon progeny compared to uranium miners [5,19]. Radford et al., stated: "...we consider that average exposures are probably accurate to ± 30 percent" [5]; thus, the true average exposure could be between 56 and 104 WLM.

Exactly how Radford and St. Clair Renard defined the cohort, and calculated or excluded the PYR, was unclear from the article. To account for a 10-year lung cancer latency, they excluded PYR for lung cancer during the first 10 years after mining was begun [5]. From their description, it is unclear when mining was begun and whether PYR were counted from the beginning of mining, January 1, 1951, or some other date. It is assumed that most of the miners' PYR were excluded from the

years prior to 1951, rather than the period 1951-1976 (years when the authors analyzed mortality), and that the mining population was stable. If one makes these assumptions (unstated by the authors), then adjusting for latency by excluding PYR during the first 10 years after the start of mining should produce unbiased SMR calculations. On the other hand, adjustments for latency that incorrectly exclude many PYR lower the expected number of deaths, thereby possibly overestimating the SMR and the risk due to radon progeny. Because of insufficient information, NIOSH is unable to completely evaluate the effect of the 10-year adjustment for latency on the SMR in this study, although it appears to be minor.

F. Fluorspar Miners in Newfoundland

1. Description

The study cohort (followed to the end of 1981) consisted of 2,120 miners, millers, and surface workers employed in the St. Lawrence, Newfoundland fluorspar mines between 1933 and 1978. Although fluorspar was not radioactive, radon gas entered the mines through contaminated ground water and produced fairly high radon progeny WL (up to 200 WL in a nonventilated area) [11]. Radon gas and progeny in the mines were first measured in 1959-60, but frequent measurements did not occur until 1968. Exposure levels had to be estimated before 1960, and from 1960 to 1967, based on these infrequent measurements, average exposures were about 0.5 WL [40]. Members of the Canadian AECB recently reestimated pre-1960 radon progeny levels based on the ventilation history of the mines, the year, type of work, and conditions under which the first measurements were made in 1959 and 1960. Radon progeny WL varied from below levels of detection to almost 200 WL in an inactive area; after the introduction of mechanical ventilation in 1960, radon progeny levels fell below 1 WL.

There were about 37,730 PY of observation (excluding PYR during the first 10 years after start of mining) for the total cohort; 25,877 for the "exposed" workers (undefined in text) [11]. Underground miners accounted for a large proportion of the total cohort PY (57 percent by the 1971 update). By 1977, there were 98 lung cancer deaths, 89 among underground workers and 9 among surface workers [40]. A survey of all men employed in 1960 indicated that these workers were heavy smokers; 86 percent were current smokers and 87 percent of the current smokers smoked at least 15 grams of tobacco (about 24 cigarettes) per day [40,41].

The entire cohort experienced 104 lung cancer deaths by 1981, versus about 24.4 expected (calculated from the mortality rates of surface workers; also, PYR during the first 10 years after underground exposure were excluded), yielding an SMR of about 426 (p value unspecified by the authors, but estimated to be $p < 0.05$ from the number of expected deaths and the Poisson frequency distribution). Using a linear model, Morrison et al. (1985) calculated an attributable risk index of 5.5-6.0 per 10^6 PY-WLM ($p < 0.10$), depending upon smoking status and adjusted for a 10-year latent period (see Glossary for definitions) [11]. Lung cancer

mortality was elevated in the 10–239 WLM ($p=0.09$) and the 240–599 WLM ($p=0.06$) cumulative radon progeny exposure categories, but significantly elevated ($p<0.05$) only above 600 WLM. In other mining epidemiology studies, excess deaths occurred at lower levels of exposure; Morrison et al. (1985) attributed this difference to the small cohort size in their study [11,12,25]. The exposure categories were 1–9, 10–239, 240–599, 600–1,079, 1,080–2,039, and 2,040+ WLM [10].

2. Strengths

One strength of this study was the long follow-up period; workers were followed for an average of about 30 years of observation [11,19]. Also, the researchers obtained smoking history data for 41 percent of the cohort [11].

3. Limitations

There were three principle limitations in this study. First, there was limited exposure data available before 1968 (See above). Second, the study failed to trace large numbers of workers; 591 workers who lacked adequate personal identifying information (name and year of birth) were dropped from the analysis. Third, this study lacks an adequate basis for estimating expected deaths. Lung cancer rate comparisons between the mining population, with its many smokers, and the Newfoundland or Canadian national populations, would exaggerate excess deaths due to radon progeny exposure. Morrison et al. (1985) tried to avoid this problem by generating the expected number of deaths among underground workers from a comparison with mortality rates among surface workers (adjusted for age, time period, and disease specific mortality) [11]. A problem with this study design is that the control group may be exposed to radon progeny. Some of the men classified as surface workers (controls) may have received some radiation exposure, by means of either misclassification or unrecorded short periods of working underground. Also, it is difficult to correctly adjust for age, time period, and disease specific mortality, when there are proportionately fewer workers in the control group (surface workers) than in the exposed group (as of 1971, underground workers accounted for 57 percent of the total person-years [40]). The lack of an adequate comparison group is a serious limitation, so risk estimates from this study must be viewed with caution.

G. Secondary Epidemiologic Studies

The ten epidemiologic studies reviewed herein examine mortality among miner populations in China, Sweden, the United States, Great Britain, France, and China. Several studies demonstrated elevated radon progeny levels and excess lung cancer deaths among underground miners, but lacked information about radon progeny exposure, or levels of other mine carcinogens. Other studies contained severe limitations or biases that also restricted their usefulness. Overall, the ten secondary studies provide additional information about the association between lung cancer mortality and radon progeny exposure, yet have more limitations (in study design, study population size, radon exposure records, thoroughness of followup, etc.)

than the five primary studies. To be concise, the secondary studies are described in less detail than the primary studies.

1. Iron Ore Miners in Grangesberg, Sweden

Edling and Axelson compared 38 lung cancer cases, of which 33 were underground iron ore miners, to 503 age-matched referents from the Grangesberg, Sweden parish (deaths occurring from 1967-77) [13]. One strength of this study was the large number of referents used by the authors. A comparison of underground workers to nonexposed individuals in the parish showed a lung cancer SMR of 1,150 ($p < 0.05$). Measurements, made in 1969-70, revealed that radon progeny levels ranged from 0.3-1.0 WL in these mines. Radon levels from 1920-69 were reconstructed from assumptions about mine ventilation and the 1960-1970 measurements; this method was the chief limitation in this study. Researchers found traces (concentration unspecified) of nickel and chromium, but no arsenicals or asbestiform minerals in the mine. Edling and Axelson estimated an attributable risk (See Glossary for definitions) of 30-40 cases per 10^6 PY-WLM for miners who were over the age of 50 (at the time of diagnosis) [13].

2. Zinc-Lead Miners in Sweden

This case referent study examined lung cancer mortality during 1956-76 among residents from the parish of Hammar, Sweden, an area with two zinc-lead mines [42]. Twenty-nine subjects who died of lung cancer, including 21 who were underground miners, were matched with three referents who died before or after each case. Some problems with the study were the small number of cases and a failure to match for age or smoking status. Axelson and Sundell (1978) reported a sixteenfold increase ($p < 0.0001$) in lung cancer mortality among the miners versus nonminers. Although they lacked individual information on exposure, they estimated a radon progeny level of about 1 WL in the mines, based on measurements made in the 1970's [42]. These results should be viewed with caution; since they demonstrated that age was a confounding factor, yet they did not match cases and referents for age.

3. Iron Ore Miners in Kiruna, Sweden

This study examined lung cancer mortality among residents of the Kiruna parish in Northern Sweden, an area containing two underground iron mines [43]. One strength of this study is that migration in the Kiruna area was slight, therefore, nearly all former miners' deaths were registered in Kiruna. From 1950 to 1970 a total of 41 men (in Kiruna) between the ages of 30-74 years died of lung cancer. Thirteen of these were underground miners, and it is possible, although unclear in the report, that 18 were surface workers. One limitation of this study is that the age distribution of underground miners was unrecorded, and therefore, proportional mortality was used instead of the life table method to calculate the expected mortality. Another limitation is that the expected mortality was not adjusted for smoking status, since information from family and fellow workers indicated that 12 of the 13 underground miners smoked (8 smoked cigarettes, 4 smoked pipes).

Jorgensen (1973) compared the 13 deaths observed among underground miners with expected deaths of 4.47, based on local rates, and 4.21, based on Swedish national rates. In both cases, he reported significantly elevated mortality ($p < 0.05$) among the underground miners [43]. Because this proportional mortality study involved few lung cancer cases, 13 for underground miners and 28 for all other men in Kiruna, the results should be viewed with caution. Radon progeny exposure records were unavailable for the underground miners, however, there were measurements of 10–100 pCi/l radon progeny (about 0.10–1.0 WL at 100 percent equilibrium).

4. Iron Ore Miners in Kiruna and Gallivare, Sweden

This case control study examined lung cancer mortality among residents in the three northernmost counties in Sweden [44]. This region contains a variety of industrial activities, including mines, smelters, steel factories, coke ovens, and paper mills. Therefore, to analyze the lung cancer risk due to underground work in iron ore mines, one should examine the lung cancer mortality among residents from Kiruna and Gallivare, Sweden municipalities, where the iron mines are located. Among these counties in Sweden, there are 604 lung cancer cases; however, when limiting the study to residents of Kiruna and Gallivare, there are 31 lung cancer cases.

Damber and Larsson (1982) used information from questionnaires, as well as the Swedish Cancer and National Registries for Causes of Death to match lung cancer cases with controls according to sex, year of birth and death, and municipality [44].

For smokers exposed to underground mining, a very high risk ratio (36.0, based on 18 lung cancer cases; p value unspecified), was reported. For smokers without underground mining experience, it was 6.9 (based on 10 cases), and for nonsmokers with and without underground mining experience, 13.3 (based on 2 cases) and 1.0 (based on 1 case), respectively. This study suggested that miners who worked underground, especially those who smoked, had elevated lung cancer risks. Due to the small number of lung cancer cases studied, this association must be viewed with caution.

5. Metal Miners in the United States

This cohort mortality study involved white male underground metal miners in the United States. The cohort was defined as miners who had completed, at a minimum, their fifteenth year of underground mining experience between January 1, 1937 and December 31, 1948. The cutoff date for mortality analysis was December 31, 1959. Altogether, the cohort contributed 25,033 PYR. The comparison group was white males from the same states. A positive feature of this study was that mortality was adjusted for age using a modified lifetable method. Wagoner et al. (1963) observed 47 lung cancer deaths against 16.1 expected, for an SMR of 292 ($p < 0.01$). The miners' exposures included 10–80 picocuries per liter (pCi/l) radon gas (about 0.05–0.40 WL at 50 percent equilibrium; based on 1958 measurements). One limitation of

this study is that the miners were also exposed to the following substances, in order of diminishing quantities: sulfur, iron, copper, zinc, manganese, lead, arsenic, calcium, fluorine, antimony and silver. There were trace amounts of nickel, yet no chromium or asbestos was found in the mines [4].

6. Navajo Uranium Miners in the United States

Samet et al. (1984) used the New Mexico Tumor Registry to identify 32 lung cancer cases among Navajo men between 1969 and 1982 [16]. For each case, on the basis of age and date of diagnosis, they matched two Navajo male controls who had died of cancer. Occupational histories were taken from USPHS records for uranium miners, registry abstracts, and death certificates. Occupational information was incomplete or missing for an unspecified number of cases and controls. The authors were able to document that 23 of the lung cancer cases had been uranium miners, while they found no similar documentation for any of the controls. Although this result is highly suggestive of an association between lung cancer and uranium mining, it is inconclusive due to the incomplete and inconsistent ascertainment of occupational histories. Samet et al. (1984) emphasized their findings of lung cancer mortality among Navaho men, because 21 of the 23 miners with lung cancer were nonsmokers or light cigarette smokers.

7. Tin Miners in Cornwall, Great Britain

This cohort study examined mortality among underground and surface miners from Cornwall, Great Britain, who were listed in the National Health Service Central Register (NHSCR) as tin miners in October 1939. The study population was 1,333 tin miners, contributing a total of 27,631 PYR between October 1939 and the end of 1976. One limitation of the study was a lack of smoking information. Another limitation was the use of NHSCR records, which do not include detailed employment histories, and thus some workers may have been misclassified as surface or underground miners. Fox et al. (1981) compared the miners' lung cancer mortality with age-adjusted mortality rates from England and Wales. For underground and surface workers together, they found 61 lung cancer deaths versus 52 expected, yielding an SMR of 117, (Fox et al., failed to calculate a p value; NIOSH estimates that this SMR is not significant). Among those known to be underground workers, there were 28 lung cancer deaths observed versus 13.27 expected (estimated from the SMR reported by Fox et al., in the text), yielding an SMR of 211 (p value unspecified in text, however, it is estimated that $p < 0.05$, from the observed deaths and the Poisson frequency distribution). The earliest radon progeny measurements, made in 1967-1968, revealed average working levels of 1.2 and 3.4. The National Radiological Protection Board (NRPB) estimated that exposure rates were 15 and 25 WLM in two Cornish tin mines (unspecified whether these were annual averages) [2].

8. Iron Ore Miners in Great Britain

This proportional mortality study examined lung cancer mortality among iron ore (haematite) miners in West Cumberland, Great Britain [45].

Lacking long-term employment records, Boyd et al. (1970) based their research on a proportional analysis of death certificate data from Whitehaven and Ennerdale during 1948 to 1967. Boyd et al. (1970) found 36 lung cancer deaths among underground miners versus expected deaths of 20.6 (estimated from local records) and 21.5 (estimated from national records). This yielded lung cancer mortality among underground miners 1.67 (p value unspecified by the authors, however, estimated at $p < 0.05$ using the number of observed deaths and the Poisson frequency distribution) to 1.74 ($p < 0.001$) times higher than expected. These results must be interpreted with caution, because they are derived only from a comparison of proportions. The researchers took age into account, but not smoking behavior; also, they lacked individual records of exposure. Measurements made in the West Cumberland haematite mines revealed radon progeny levels ranging from 0.15–3.2 WL [45]; Boyd et al. (1970) said that the average radon gas concentration was 100 pCi/l (about 0.50 WL at 50 percent equilibrium) [45].

9. Uranium Miners in France

Tirmarche et al. (1985) presented a preliminary analysis of mortality among a cohort of men who had at least 3 months underground mining experience, and who started to work in uranium mines between 1947 and 1972 [47]. Only four mines were open in France during 1947–1972. One strength of this study is the thorough recordkeeping of miners' exposures to radon gas, radioactive ore dust concentrations, and gamma radiation. For the period 1947–1955, there were no radon measurements available, however, a committee of experts estimated average monthly radon progeny exposures varied from 1–10 WLM. In 1956, 7,470 radon gas measurements were collected. From 1957 to 1970, about 20–30 radon gas measurements were collected per miner per year; from 1970 to the present, 57–70 per miner, per year. The only limitation of these records is that they are based on radon gas, rather than direct radon progeny measurements. At present, the mean factor of equilibrium in the French mines is 0.22. The miners' average annual radon progeny exposures varied from 2.5 to 4.3 WLM during 1956 to 1970 and 1.6 to 3.2 WLM during 1970 to 1980; these exposures may be comparable to those that uranium miners in the United States receive under a 4 WLM standard.

PYR were calculated for each miner from the day of entry in the mine, until the date of his death or until December 31, 1983. In this preliminary report, 1,957 miners accumulated 22,394 PYR during 1947–1980, an average of 11.4 years of underground mining per miner [47]. Tirmarche et al. (1985) reported 36 observed deaths in the cohort versus 18.77 expected (based on age-adjusted national rates) yielding an SMR of 191 ($p = 0.0002$). Tirmarche et al. (1985) are presently collecting data on the miners' smoking habits. When it is completed, this should be one of the best epidemiologic studies available for examining mortality among miners receiving low radon progeny exposures.

10. Tin Miners in Yunnan, China

Jingyuan et al., and Wang et al., conducted a 7-year (1975–81) epidemiologic survey of 12,243 men who had worked underground in Chinese

tin mines [48,49]. From 1975-81, there were 499 cases of lung cancer among men who had worked underground; their mean cumulative radon progeny exposures totaled 716 WLM (range 19-1945 WLM), and they worked a mean of 24 years in the mines [49].

From 1975-81, Wang et al. (1984) observed 433 underground miner lung cancer deaths, versus 29.8 expected (generated from rates in Shanghai males), for an SMR of 1,451 (p value unspecified by the authors, however, estimated at $p < 0.05$ from the number of observed deaths and the Poisson frequency distribution) [49]. There were a total of 86,136 "detriment man years" (undefined in text) among the deceased miners. Wang et al. (1984) estimated a "risk coefficient" of 6.6×10^{-6} /year WLM (undefined in text).

There were many excess lung cancers at low radon progeny exposures, i.e., an SMR of 436 (p value unspecified by the authors, however estimated at $p < 0.05$, from the number of observed deaths and the Poisson frequency distribution) at cumulative exposures below 140 WLM. Arsenic concentrations in ore samples were high, 1.50-3.53 percent [49]. For the years 1950-59, it was estimated that a miner inhaled 1.99-7.43 mg arsenic per year [48]. The authors suggested that the high arsenic content in the ore samples may cause lung cancer [49].

The strength of this study lies in the large number (12,243) of underground miners studied. One limitation is that the study cohort is ill-defined; the study design mixes aspects of a survey for incidence with a cohort study. Wang et al. (1984) [49] fail to describe when the workers started mining and how many were lost to follow-up; also, whether the 12,243 miners worked between 1975-81 or constituted all tin miners who ever worked underground. The major limitation appears when comparing these studies with other mining research studies because Wang and associates handled radon progeny measurement techniques and epidemiologic methods in a different manner. For instance, they did not mention if their mortality statistics were adjusted for age or smoking status. Their comparison population, male residents in urban Shanghai municipality, has much higher lung cancer rates than males in rural Yunnan province [50]. Therefore, the Shanghai comparison group was inappropriate and may have underestimated these miners' lung cancer risks.

Another limitation is that arsenic exposure has been associated with lung cancer among copper smelter and pesticide workers [8,9]. This research may be most useful for studying the interaction of two carcinogens, arsenic and alpha radiation from radon progeny, rather than for studying radon progeny lung cancer risks alone.

H. Smoking

The two most thorough studies of the interaction between smoking and radon progeny exposure are those by Whittemore and McMillan (1983), using the U.S. white uranium miners data set [14], and by Radford and St. Clair Renard (1984) using the Swedish iron miners data set [5]. The major flaw in other studies of the interaction between smoking and radon progeny exposure

[13,16,42,51] is an inadequate sample size of miners with both exposure records and smoking histories.

1. Uranium Miners in the United States

Whittemore and McMillan (1983) examined lung cancer mortality among the white USPHS uranium miners cohort, based on a mortality follow-up through December 31, 1977. In their analysis, they included nine additional miner lung cancer deaths which occurred after December 31, 1977, for a total of 194 lung cancer cases [14] (see section III.B).

For each case, four control subjects were randomly selected from among those white miners born within 8 months of the case and known to survive him, yielding a total of 776 matched controls [14]. A regression analysis of the radon progeny exposure and smoking data for cases and controls revealed that the data fit a multiplicative linear relative risk model $[R=(1+B_1WLM)(1+B_2PKS)]$, but showed "significantly poor fit" ($p<0.01$) for the additive linear relative risk model $[R=1+B_1WLM+B_2PKS]$ [14]. The data demonstrated a synergistic effect, that is, the combined action of smoking and radon progeny was greater than the sum of the actions of each separately.

Whittemore and McMillan, based on the multiplicative linear relative risk model $[R=(1+B_1WLM)(1+B_2PKS)]$, suggested that miners who have smoked 20 pack-years of cigarettes (excluding tobacco use within the past 10 years) experience radiation-induced lung cancer rates per WLM that are roughly five times those of nonsmoking miners [14]. (They estimated that B_1 , the excess relative risk per unit of radon progeny, was 0.31×10^{-2} and B_2 , the excess relative risk per unit of cigarette smoke exposure, was 0.51×10^3).

2. Iron Miners from MalMBERGET, Sweden

Radford and St. Clair Renard (1984) calculated smoking-adjusted rate ratios for miners [5]. Using both the known rate ratio of lung cancer for smokers versus nonsmokers and the proportions of smokers in Sweden, Radford and St. Clair Renard estimated the Swedish national lung cancer rates for smokers and nonsmokers (age and calendar year adjusted). These smoking specific national lung cancer rates were used to generate numbers for observed and expected deaths. Radford and St. Clair Renard (1984) estimated a rate ratio for smoking miners of 2.9 (90 percent confidence limits, 2.1-3.9; 32 observed/11 expected), and 10.0 for nonsmoking miners (90 percent confidence limits, 6.5-14.8; 18 observed versus 11.8 expected), compared to the national population. They found that the combined effect of smoking and radon progeny exposure in these miners was additive.

3. Conclusions Related to the Interaction of Radon Progeny Exposure and Smoking

Studies of white uranium miners in the United States [14], and iron miners in Sweden [5], support different models of risk due to radon progeny and smoking; the first supports a multiplicative model, the

second, an additive model. These two studies arrive at different conclusions which is not surprising, given the differences in statistical methods, cumulative exposure levels (the averages differed by a factor of 10), smoking histories, and method of calculating expected deaths between the studies. Whittemore and McMillan (1983) [14] used lung cancer rates among age and birth cohort matched miners; Radford and St. Clair Renard (1984) [5] used smoking-adjusted national lung cancer rates. A longer follow-up in the study of uranium miners in the United States may change the relative risk estimates but probably not to the degree necessary for an additive relationship. In Radford and St. Clair Renard's analysis, they apparently used crude linear corrections for the proportion of smoking as a function of age in order to allocate person-years weighted for smoking. Their figures were uncorrected for amount or duration of smoking, these simplifications may well have masked the "true" smoking-radon progeny relationship [52].

Based on the presently available information, it is impossible to conclude whether the additive or multiplicative model is the best. Nevertheless, present research indicates a higher risk from combined exposure; data from both radiation exposure and smoking histories are essential for an accurate estimation of radiogenic lung cancer risks.

I. Discussion and Conclusions Related to the Epidemiologic Evaluation

1. The Five Primary Epidemiologic Studies

The five primary epidemiologic studies that examine lung cancer mortality among underground miners are the studies of uranium miners in the United States, Czechoslovakia, and Ontario, as well as iron miners in Sweden and fluorspar miners in Newfoundland. Despite the individual limitations of each study, the association of radon progeny exposure and lung cancer was shown to persist for all five studies, using different study populations and methodologies. There was an elevated lung cancer SMR and a dose-response relationship for radon progeny exposure and lung cancer among the five underground miners' cohorts; the higher the estimated radon progeny exposure, the greater the number of excess deaths. Some studies [3,5,14] adjusted their mortality figures for the estimated latency of radiogenic lung cancer, yet the association between lung cancer cases and radon progeny exposure remained.

Table III-2 is a summary of the observed and expected deaths and the SMR's in the five studies. These studies handled adjustments for latency, lagging dose, smoking history, or age as detailed in the footnotes in Table III-2. As yet, there is no one standard method to adjust person-years, expected deaths, or SMR's, or even agreement that these parameters should be adjusted.

All five studies [3,5,10,11,12] lacked adequate radon progeny exposure data for individuals because, in general, these data were originally collected for monitoring, and not research purposes. In addition, some studies [5,10] based the exposure assessment upon radon gas measurements, which must be converted to radon progeny estimates. It is reasonable, however, to extract what information is available from these

TABLE III-2: THE FIVE PRIMARY EPIDEMIOLOGIC STUDIES

| Epidemiologic Studies | References | Mean Dose (Cumulative WLM) | Person-Years (PY) | Lung Cancer Deaths | | |
|---|--|----------------------------|----------------------|--------------------|--------------------|------------------|
| | | | | OBS | EXP | SMR ^a |
| U.S. Uranium Miners | Waxweiler et al. (1981) [14] | 821 (median=430) | 62,556 | 185.0 | 38.4 | 482 |
| Czechoslovakian ^b Uranium Miners | Placek et al. (1983) [22] Kunz et al. (1978) [23] | 289 | 56,955 | 211.8 | 42.7 | 496 |
| Ontario Uranium Miners | Mueller et al. (1985) [3] | 40-90 ^c | 202,795 ^c | 82 ^c | 56.9 ^c | 144 |
| Swedish Iron Miners | Radford & St. Clair Renard (1984) [5] | 81.4 ^d | 24,083 ^d | 50 | 12.8 ^d | 390 ^d |
| Newfoundland Fluorspar Miners | Morrison et al. (1985) [10] | — ^e | 37,730 ^e | 104 | 24.38 ^e | 427 ^e |

FOOTNOTES:

- a. $p < 0.05$ P-values were unspecified by Mueller et al., (1985) [3], Radford and St. Clair Renard (1984) [5], and Morrison et al., (1985) [10]. They were estimated from the observed lung cancer deaths and the Poisson frequency distribution.
- b. Based on the subcohort of uranium miners who started mining 1948-52, "group A" miners.
- c. Uranium miners with no prior gold mining experience. It is unclear from the article [3] whether the authors lagged the dose to calculate cumulative exposures.
- d. PY for the first 10 years after start of mining were excluded; expected deaths were also adjusted for smoking status. Dose was lagged by 5 years.
- e. Includes PY for surface, as well as underground, miners. Radon progeny exposure levels were recently reestimated [10]. PY for the first 10 years after start of mining were excluded in the calculation of expected deaths and PY.

five studies, rather than eliminate a particular study because of exposure data quality.

The primary studies of iron miners in Sweden and uranium miners in Czechoslovakia searched for other exposures [9,53,54] (i.e., mineral ores, radiation, diesel fumes) in the mining environment. The Czechoslovakian uranium mines contained various amounts of arsenic, but only trace amounts of chromium, nickel, and arsenic [7,9,53,54]. Researchers examined lung cancer mortality in two uranium mining localities that had similar radon progeny levels, but a fiftyfold difference in arsenic concentrations. They failed to find a significant difference in mortality between the two groups of miners [27,28,29,30,31], concluding that arsenic was not affecting the lung cancer rates of underground miners in Czechoslovakia. Arsenic, chromium and nickel were essentially absent in the Swedish iron mines. There were occasional inclusions of serpentine, but no identifiable asbestos fibers in dust samples [5]. The Swedish iron mines contained iron ore dust, but Stokinger (1984), after review of the literature from health reports involving underground iron ore miners, iron and steel workers, foundrymen, welders, workers in the magnetic tape industry, and others, concluded that these studies failed to clearly demonstrate the carcinogenicity of iron oxide dust [55].

The influence of other types of radiation present in the mines, such as long-lived alpha, beta, and gamma radiations, cannot be determined from these five studies. The miners do not show an excess mortality from leukemia, a disease linked to high gamma radiation exposures [1,3,15]. Most of the studies provided insufficient information about diesel fume exposures in the mines, so that it is impossible to reach conclusions regarding the effect of diesel fume exposure upon lung cancer risk. In the Swedish iron mines, 70 percent of miners with lung cancer left underground work or died before diesel equipment was introduced in the 1960's; the remaining miners had brief diesel fume exposures immediately before death [5]. Therefore, diesel fume exposure could not account for the excess mortality in the Swedish cohort [5]. Cigarette smoke appears to be the most important carcinogen common to the five primary studies. The proportion of cigarette smokers among underground miners in the United States, Newfoundland and Sweden was greater than among the general male population in those countries [5,12,40]. The influence of possible carcinogens in mines (in addition to radon progeny) upon lung cancer mortality needs further research.

2. The Ten Secondary Epidemiologic Studies

Ten epidemiologic studies were identified by NIOSH as secondary studies, which strengthen the association between excess lung cancer mortality and radon progeny exposure, yet have more limitations (in study design, radon exposure records, follow-up, etc.) than the five primary studies. The ten epidemiologic studies examined lung cancer mortality among underground iron ore and zinc-lead miners in Sweden, metal and Navaho uranium miners in the United States, tin and iron ore miners in Great Britain, uranium miners in France, and tin miners in China. All ten studies have incomplete radon progeny exposure records. Nevertheless,

all reported an elevated lung cancer mortality in underground miners and the presence of radon progeny in the mines. The studies of metal miners in the United States [4], and tin miners in China [49] also found arsenic in the mines; Wang et al. (1984) suggested that the high arsenic content of the ore may be a cause of lung cancer [8,9,49]. The study of tin miners in China found an exposure-response relationship between cumulative radon progeny exposure and excess lung cancer mortality, but at the lowest exposure level (less than 140 WLM), still found an unusually high SMR (436) [49]. The arsenic exposures of these underground miners may contribute to the high lung cancer SMR; arsenic exposure is associated with lung cancer in copper smelter and arsenical pesticide workers [8,9].

The study of iron ore miners in Grangesberg, Sweden estimated an attributable risk of 30-40 cases per 10^6 PY-WLM for miners over the age of 50 [13]. This attributable risk estimate is comparable to that reported by Radford and St. Clair Renard (1984) for miners in Malmberget, Sweden in the same age group [5].

3. The Lowest Cumulative Radon Progeny Exposures Associated with Excess Lung Cancer Mortality

The five primary epidemiologic studies are far from completion, since the cohorts' follow-ups are truncated. For example, the uranium miners in the United States were followed a mean of 19 years (by 1977), while the iron miners in Sweden were followed a mean of 44 years (the Swedish study has the longest follow-up period of the five primary studies). Lung cancer rarely is manifested before age 40, regardless of etiology [20,35].

Frequently, the initial analyses performed on a cohort lack enough PYR and statistical power to show a statistically significant association between excess lung cancer mortality and low radon progeny exposure levels. Later analyses accumulate additional PYR for the entire cohort and specific subgroups, increasing the ability to detect an effect due to radon progeny. This point is important when determining the lowest radon progeny exposures associated with excess lung cancers. A longer follow-up period, resulting in more PYR and statistical power in a study, may reveal an association between excess lung cancer mortality and radon progeny at lower cumulative exposures.

The study of uranium miners in the United States by Lundin et al. (1971) [12] had an average of about 10 years of follow-up (by 1968) and found excess cancers above 120 WLM. The study of uranium miners in Czechoslovakia found excess mortality above 100 WLM [10,24]. Two recent studies, of miners in Ontario and Sweden, reported excess cancers at cumulative radon progeny exposure levels of 40-90 WLM and 80 WLM, respectively [3,5]. Thus, two epidemiologic studies found excess lung cancer mortality associated with radon progeny exposure levels below 100 WLM.

In addition, studies suggest that both radon progeny exposure and smoking are involved in the lung cancer mortality of underground miners;

however, the available information does not allow one to state whether radon progeny and smoking interact in an additive or multiplicative fashion [5,14]. One estimate is that miners who smoked 20 pack-years of cigarettes have radiation-induced lung cancer rates per WLM that are roughly five times those of nonsmoking miners [14].

Finally, the five primary and ten secondary mining epidemiologic studies all demonstrate excess lung cancer mortality among underground miners working in the presence of radon progeny.

IV. MEDICAL SCREENING AND SURVEILLANCE OF UNDERGROUND MINERS EXPOSED TO SHORT-LIVED ALPHA PARTICLES

A. Qualities of Effective Medical Screening and Surveillance

It is not clear what protects one person and not another, given comparable exposure to a carcinogen. Thus, it is important to develop valid and reliable tests that can (1) recognize the early signs of the effects of exposure to serious occupational hazards with prolonged induction-latency periods, and (2) detect these abnormalities in asymptomatic individuals at a reversible stage.

Recent reviewers describe the principles and criteria which should underlie the design, conduct, interpretation, and evaluation of medical screening programs for respiratory disease and cancer in occupational settings [56,57,58,59,60,61,62,63,64]. At the current state of knowledge, routine periodic chest X-rays and sputum cytologic examinations fail to meet the criteria for suitable screening tests to prevent radiation-induced lung cancer (See Table IV-1). In fact, lung cancer appears to be an unsuitable occupational disease for screening given the current state of knowledge about its early recognition and treatment (See Table IV-2).

B. Screening and Lung Cancer Prevention

Alpha radiation-induced lung cancer may be preventable (by limiting exposures to radon and thoron progeny) but not treatable. By the time radiogenic lung cancer is detected among individuals in an exposed work force by routine periodic screening, the affected workers fail to benefit from any further preventive or therapeutic measures.

Available screening tests may detect radiation-induced, premalignant abnormalities in asymptomatic exposed workers years before disease appears. At the current state of knowledge, however, it is unknown whether medical removal of asymptomatic workers with these abnormalities will prevent progression to malignant disease. A recent study by NIOSH tested the within-reader reliability of an expert in sputum cytologic and histopathology. The reader reliably detected malignant changes, but frequently read early changes as "pre-malignant" on one occasion and as "within normal limits" on other occasions [65].

To date, there is no convincing evidence that routine periodic medical screening of workers exposed to pulmonary carcinogens is an effective means of prevention of mortality due to lung cancer in these workers. Coke oven workers are presently the only group of workers covered by a mandatory rule for periodic screening by sputum cytology and chest X-rays. Although the effectiveness of that regulation has not yet been evaluated, such studies are now underway. In addition, NIOSH is currently collecting data on lung cancer rates and the results of sputum cytologic tests for some miners in the USPHS cohort [66]. Also, frequent exposures of underground miners to chest X-rays for screening purposes are not recommended at present.

TABLE IV-1. CRITERIA FOR DETERMINING THE SUITABILITY OF A CANCER SCREENING TEST FOR USE IN THE WORKPLACE

| Coles and Morrison (1980) [61]: | Halperin et al. (1984) [62]: |
|---|---|
| <p>1. The test should be "effective" in terms of its validity, reliability, sensitivity, specificity, and operational characteristics (such as predictive value).</p> <p>2. The test should be "acceptable" to workers in terms of its cost, convenience, accessibility, lack of morbidity.</p> | <p>1. The test should be "effective" in terms of its validity, reliability, sensitivity, specificity, and operational characteristics (such as predictive value).</p> <p>2. The test need not be uncomplicated or inexpensive, but its performance and interpretation must be done by competent professionals.</p> <p>3. The test must be "acceptable" to workers in terms of its cost, convenience, accessibility, lack of morbidity.</p> <p>4. The test results must be evaluated by comparison to a suitable population, not necessarily the general population.</p> <p>5. Action levels and related medical decisions must be determined in advance of screening (based on #1 above).</p> |

Adapted from [61,62]

TABLE IV-2. CRITERIA FOR DETERMINING DISEASES SUITABLE FOR CANCER SCREENING IN THE WORKPLACE

| Coles and Morrison (1980)[61] | Halperin et al. (1984)[62] |
|--|--|
| <p>1. The disease has serious consequences.</p> <p>2. Effective treatment is available if asymptomatic disease is detected.</p> <p>3. Detectable preclinical phase must be highly prevalent among screened population.</p> | <p>1. The disease has important individual and public health consequences.</p> <p>2. Disease need not be treatable, but must be preventable.</p> <p>3. A detectable preclinical phase (DPCP) must exist and a target population (exhibiting a high prevalence of DPCP) be identified.</p> <p>4. Follow-up care (diagnostic, treatment, and social services) must be available.</p> <p>5. Natural history of the disease determines the feasibility and frequency of testing.</p> |

Adapted from [61,62]

A review of studies reporting histopathologic associations with radon progeny exposures lacked sufficient information to conclude definitely that only one specific lung cancer cell type was associated with these exposures [67]. In addition, a case-control study using data from the Third National Cancer Survey found that cigarette smoking was significantly associated with all three histologic types of lung cancer [68]; the relationship with small-cell carcinoma was strongest overall (odds ratio = 5.1), whereas those with squamous and adenocarcinoma were approximately equivalent (odds ratio = 3.1). The issue of histopathologic associations with radon progeny exposures needs further research, especially considering that many underground miners smoked cigarettes.

Both cessation of smoking [69] and reduction of the radon progeny exposures of underground miners will lower their risks for lung cancer.

C. Recommendations

1. Smoking

Since it appears that inhaled radon progeny either add to or multiply the underlying high lung cancer risk in smokers, a smoking cessation program is recommended. The combined effects of a lower (more protective) Permissible Exposure Limit (PEL) and cessation of cigarette smoking [69] would probably provide a significant reduction in lifetime risks.

2. Lung Function Tests

A baseline chest X-ray and annual spirometric lung function tests, performed and interpreted according to the criteria of NIOSH or the American Thoracic Society, would be appropriate for medical decision-making concerning job placement, medical removal protection, and disability compensation should work-related respiratory problems develop at a later time.

3. X-ray Screening

While chest X-ray screening is not an effective means of prevention of death due to occupational lung cancer, examination at 5-year intervals, and industry-wide analyses of the results of such tests may be an effective means of supplementing the primary prevention of other lung diseases, such as pneumoconioses.

4. Radiation Exposure Records

The lifetime radiation exposure record of underground miners should include information about the dose and frequency of medical irradiation. If radiation exposed workers are routinely screened for lung diseases by baseline and periodic follow-up chest X-rays, they will receive an average of about 0.025 rad per examination of external X-irradiation (where an "examination" consists of a postero-anterior and a lateral exposure) [70].

If examinations are conducted every 5 years, the average lung dose would be about 0.005 per year. Furthermore, because of the frequency of on-the-job accidents and injuries in underground mining [15], underground miners may receive considerably more medical X-irradiation over a working lifetime than workers exposed to other sources of ionizing radiation. For each of the following diagnostic examinations, the approximate X-ray dose to the lung is indicated in parentheses: thoracic spine (0.421 rad), ribs (0.324 rad), lumbar spine (0.133 rad), one shoulder (0.039 rad), lumbosacral spine (0.035 rad), and skull (0.002 rad) [70].

Given the available technology, it is important to keep radiation exposure records, both occupational and nonoccupational, for the individual worker. Personal alpha dosimetry systems are being tested in the French and Canadian uranium mines [71,72]; these may be useful in U.S. mines, when practicable.

In summary, a program of medical screening and surveillance could be an appropriate adjunct to reductions in individual radon progeny exposures. Such a program, to be an effective "secondary" preventive measure, must be: (a) mandatory on an industry-wide basis (for uranium and nonuranium miners with potential radon progeny exposures); (b) organized, conducted, and epidemiologically evaluated according to principles proposed by Halperin et al. (1984) [63]; and (c) protective of the individual miner's personal identification.

V. FEASIBILITY OF LOWERING THE STANDARD

This section examines the feasibility of lowering the current radon progeny exposure standard, including differences between current exposures and lower projected standards.

A. Comparison of Current U.S. Underground Miner Radon Progeny Exposures with Different Standards

The uranium mining industry in the United States has recorded the annual exposures of underground miners, and the Atomic Industrial Forum (AIF) figures are displayed in Appendix Tables A-9 to A-11. There has been some discrepancy between MSHA records and AIF records [73]. Overall, the industry has been successful in controlling exposures to 4 WLM. Furthermore, the percentage of miners exposed to 3 WLM or higher decreased between 1973 and 1982 (Tables A-9 to A-11, [74]).

There has been substantial mobility among the uranium miners, with many people working for short periods of time at different mines, so that the AIF separated the annual exposure data into two sets, "all persons assigned to work underground" and "persons who worked underground 1,500 hours or more" i.e., full time. It appears that, for most underground uranium mine workers, the mining industry already can meet a radon progeny standard below the current level of 4 WLM annual exposure. If the radon progeny exposure standard was set at 1 WLM, approximately one-third of all underground workers and less than two-thirds of the full-time underground workers would be exposed above a 1 WLM standard (based on 1982 figures [74]). If the exposure standard was set at 2 WLM, only about 9 percent of all underground workers and 16 percent of full-time underground workers would be exposed above 2 WLM [74]. During 1982, the AIF recorded only about 46 employees (or approximately 1.7 percent of all underground workers) with annual exposures above 3 WLM [74]. Therefore, it should be technically feasible for the mining industry in the United States to reduce the radon progeny exposures of this relatively small group of miners.

The uranium industry in the United States is currently in a period of retrenchment, as explained by analysts from the United States Environmental Protection Agency (EPA) [75]:

The uranium mining industry has undergone substantial changes in recent years due to declining demand and competition from low-cost foreign sources. The total number of all types of uranium mines in operation fell from a peak of 432 in 1979 to 135 in 1983. The number of underground mines fell from 300 in 1979 to 95 in 1983, and to 26 by November 1984. By January 1985, only 17 underground uranium mines were operating, and further reductions are expected during 1985. Production of uranium oxide by underground mines fell from a peak of 9,600 tons in 1980 to 4,100 tons in 1983.

In the case of nonuranium mines in the United States, it is clear they can meet a lower exposure standard, based on the limited data submitted by the mining companies to MSHA (Appendix Table A-5).

Of those nonuranium mine workers whose exposures to radon progeny were recorded, the upper limits of exposure varied from 0.16 to 2.20 WL, depending upon the mining industry (Appendix Table A-1). Acknowledging the limitations on the way exposure data is collected (Appendix A, section A.2.a.), the mining companies submitted information to MSHA which suggests that no more than 450 individuals are occasionally exposed to substantial radon progeny levels (i.e., 0.3 WL and above) (Appendix Table A-5). During 1983, these radon progeny exposed employees were found in only 4 nonuranium mines, out of a total of about 574 U.S. nonuranium metal and nonmetal underground mines. Therefore, it should be feasible to control the radon progeny exposures encountered by these 450 (or fewer) miners.

B. The Technological Capacity to Further Reduce Exposure

Some of the highest radon progeny exposures are received by people working in the smallest uranium mines, those employing less than ten people [73]. Probably, these small mines can improve their ventilation systems and reduce worker exposures. Currently, many of these small mines are not operating due to the depressed prices for uranium.

There are a variety of techniques besides ventilation that can reduce workers' radiation exposures (Appendix B). In general, these techniques are more costly and less effective than ventilation. Nevertheless, these methods, in addition to ventilation, could be used to decrease the exposures of the relatively small number of uranium workers (46 during 1982) [74] who currently receive more than 3 WLM annually.

The Bureau of Mines (BOM) recently contracted with Bloomster et al. (1984) from the Battelle Pacific Northwest Laboratories for an analysis of the technical feasibility and costs for lowering the current radon progeny standard in underground uranium mines [76]. Presently, this report is only available in draft form and the final report's findings may differ from those mentioned herein. Given the possibility that the mining companies that volunteered for the study are not representative of the industry as a whole, the Battelle investigators found that, from a technical standpoint, most underground uranium mines could not meet a standard of 0.5 WLM, would have problems meeting a standard of 1 WLM using dilution ventilation alone, but could meet a standard of 2 WLM. However, a limited study of two mines suggested that it might be technically feasible to meet a standard of 1 WLM using dilution ventilation in combination with other control methods, especially bulkheads [76].

Finally, based on workers' current annual exposures and an engineering analysis, it is technically feasible to lower underground miners' exposures to radon progeny below the present annual standard of 4 WLM. The mining industry recorded only 46 uranium miners with exposures above 3 WLM and none with exposures above 4 WLM during 1982. Only 450 (or fewer) nonuranium miners are occasionally exposed to radon progeny levels of 0.3 WL or above. It should be technically feasible for the mining industry to control the

radon progeny exposures of these relatively few workers receiving substantial exposures. Also, an engineering analysis (based on data from only two mines) suggested that it is technically feasible for uranium mines to meet a standard as low as 1 WLM, using control techniques such as ventilation, bulkheads, and backfilling.

VI. CONCLUSION

Each of the five primary epidemiologic studies contained strengths and limitations. All of the studies [3,5,10,11,12] rely on incomplete radon progeny exposure estimates to calculate the cumulative exposures of the underground miner cohorts. Nevertheless, they contain sufficient strength to demonstrate an excess lung cancer risk associated with radon progeny exposure. Also, an exposure-response relationship exists between cumulative radon progeny exposure and lung cancer mortality [3,10,11,12,24]. Statistically significant SMR's above 400 were observed in three studies, where workers accumulated mean exposures above 100 WLM [10,11,15,24]. Statistically significant SMR's between 140 and 390 were observed in two studies [3,5], where workers accumulated mean exposures below 100 WLM, and in preliminary findings from a third study by Tirmarche et al. (1985) where workers probably accumulated mean exposures below 100 WLM [47].

NIOSH acknowledges the efforts of various groups [19,21,35,77] to compare attributable and relative risk estimates across different epidemiologic studies. NIOSH can neither validate nor refute these findings. At this point, without access to the raw data and more specific information about epidemiologic methods, NIOSH is unwilling to speculate or make comparisons between the attributable or relative risk estimates in the five primary studies.

There were several classifications for identifying a substance as a carcinogen. Such classifications have been developed by the National Toxicology Program [78], the International Agency for Research on Cancer [79], and OSHA [80]. The OSHA classification is the most appropriate for use in identifying carcinogens in the workplace. This classification is outlined in 29 CFR 1910.103 [80].

"Potential occupational carcinogen" means any substance, or combination or mixture of substances, which causes an increased incidence of benign and/or malignant neoplasms, or a substantial decrease in the latency period between exposure and onset of neoplasms in humans or in one or more experimental mammalian species as the result of any oral, respiratory or dermal exposure, or any other exposure which results in the induction of tumors at a site other than the site of administration. This definition also includes any substance which is metabolized into one or more potential occupational carcinogens by mammals.

Since exposure to radon progeny has been shown to produce lung cancer in underground miners, it meets the OSHA criteria; thus, radon progeny should be considered an occupational carcinogen.

Data on the current radon progeny exposures of uranium, metal, and nonmetal miners suggests that the mining industry, overall, is already capable of meeting a radon progeny standard below the current annual limit of 4 WLM. Recent limited research (based on data from only 2 mines) suggests that,

using ventilation, bulkheads, and backfilling, it is technically feasible for mines to meet a standard as low as 1 WLM.

At the present time, there is no effective medical method to prevent or treat lung cancer to radon progeny exposure. Also, there is insufficient evidence to support an association between a specific lung cancer cell type and radon progeny exposure [67,68]. Only exposure prevention measures are effective in lowering radon progeny induced lung cancer rates.

These preventive measures include lowering the radon progeny exposures of underground uranium miners (and perhaps some underground metal and nonmetal miners), especially those that receive annual cumulative exposures near the present limit of 4 WLM. An additional measure is to encourage miners to stop smoking, because smoking and radon progeny exposure may act multiplicatively, or at least additively, to cause lung cancer.

Finally, a lowering of exposure, especially for the workers currently exposed near 4 WLM, is recommended. Recent information suggests that it is technically feasible to control radon progeny exposures to levels as low as 1 WLM. NIOSH wishes to withhold a recommendation for a specific PEL, until completion of a quantitative risk assessment, which is now in progress. In addition, the specific medical recommendations listed in Chapter IV should be implemented.

REFERENCES

1. Shapiro J. Radiation protection—A guide for scientists and physicians. Harvard University Press, Cambridge, 1981;480.
2. Fox AJ, Goldblatt P, Kinlen LJ. A study of the mortality of Cornish tin miners. *Br J Ind Med* 1981;38:378-380.
3. Muller J, Wheeler WC, Gentleman JF, Suranyi G, Kusiak R. Study of Mortality of Ontario Miners. In: Stocker H, ed. Proceedings of the International Conference (in two volumes), Vol I: Occupational radiation safety in mining. Toronto: Canadian Nuclear Association, 1985:335-343.
4. Wagoner JK, Miller RW, Lundin FE, Fraumeni JF, Haij ME. Unusual cancer mortality among a group of underground metal miners. *New Eng J Med* 1963;269:284-289.
5. Radford EP, Renard KGSC. Lung cancer in Swedish iron miners exposed to low doses of radon daughters. *N Eng J Med* 310:1485-1494.
6. Sevcova M, Sevc J, Thomas J. Alpha irradiation of the skin and the possibility of late effects. *Health Physics* 1978;35:803-806.
7. Sevc J, Kunz E, Placek V, Smid A. Comments on lung cancer risk estimates. *Health Phys* 1984;46:961-964.
8. Axelson O. Arsenic compounds and cancer. In: Vainio V, Sorsa M, Hemminki K, eds. Occupational cancer and carcinogenesis. Washington: Hemisphere Publishing Corp., 1980;1229[309]-1235[315].
9. Criteria for a recommended standard....occupational exposure to inorganic arsenic. Cincinnati: U.S. Department of Health, Education and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, 1975; DHEW (NIOSH) publication no. 75-149.
10. Sevc J, Kunz E, Placek V. Lung cancer in uranium mines and long-term exposure to radon daughter products. *Health Phys* 1976;30:433-437.
11. Morrison HI, Semenciw RM, Mao Y, et al. Lung cancer mortality and radiation exposure among the Newfoundland fluorspar miners. In: Stocker H, ed. Proceedings of the International Conference (in two volumes), Vol I: Occupational radiation safety in mining. Toronto: Canadian Nuclear Association, 1985:365-368.
12. Lundin FE, Wagoner JK, Archer VE. Radon daughter exposure and respiratory cancer. In: Quantitative and temporal aspects. United States Department of Health, Education and Welfare (USDHEW), National Institute for Occupational Safety and Health (NIOSH), National Institute of Environmental Health Sciences (NIEHS), Joint Monograph, No. 1, 1971.

13. Edling C, Axelson O. Quantitative aspects of radon daughter exposure and lung cancer in underground miners. *Br J Ind Med* 1983;40:182-7.
14. Whittemore AS, McMillan A. Lung cancer mortality among U.S. uranium miners: A reappraisal. *J Natl Can Inst* 1983;71:489-499.
15. Waxweiler RJ, Roscoe RJ, Archer VE, et al. Mortality followup through 1977 of the white underground miners cohort examined by the U.S. Public Health Service, In: M. Gomez, ed. Radiation hazards in mining, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc. New York 1981;823-830.
16. Samet JM, Kutvirt DM, Waxweiler RJ, Key CR. Uranium mining and lung cancer in Navajo men. *N Engl J Med* 1984;310:1481-1484.
17. Meinhardt T, Roscoe R. Personal communication based on an evaluation of the United States Public Health Service, National Institute for Occupational Safety and Health exposure data set, (November 30, 1984).
18. Hornung RW, Roscoe RF. Comments on ANPR issued by MSHA concerning radiation standards for metal and nonmetal mines. [Memorandum to Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer from Division of Surveillance, Hazard Evaluations, and Field Studies, Statistical Services Branch, and Industrywide Studies Branch, March, 5, 1985.
19. Thomas DC, McNeill KG. Risk estimates for the health effects of alpha radiation. Ottawa, Canada: Atomic Energy Control Board, 1982.
20. National Academy of Sciences (NAS) Committee on the Biological Effects of Ionizing Radiations (BEIR). The effects on populations of exposure to low levels of ionizing radiation. Washington, National Academy Press, 1980.
21. National Council on Radiation Protection and Measurements (NCRP) Report #78. Evaluation of occupational and environmental exposures to radon and radon daughters in the United States. Bethesda, MD: NCRP, 1984.
22. Sevc J, Placek V, Jerabek J. Lung cancer risk in relation to long-term radiation exposure in uranium mines. Proceedings of the Fourth Conference on Radiation Hygiene, CSSR-1971.
23. Placek V, Smid A, Sevc J, Tomasek L, Vernerova P. Late effects at high and very low exposure levels of the radon daughters. In: Broerse, JJ Barendsen GW, Kal HB, Vanderkogel AJ eds. Radiation research - Somatic and genetic effects. Proceedings of the Seventh International Congress of Radiation Research, Amsterdam, July 3-8, 1983.
24. Kunz E, Sevc J, Placek V. Lung cancer mortality in uranium miners (methodological aspects). *Health Phys* 1978;35:579-580.

25. Kunz E, Sevc J, Placek V, Horacek J. Lung cancer in man in relation to different time distribution of radiation exposure. *Health Phys* 1979;36:699-706.
26. Sevc J. Development of hygienic occupational protection in Czechoslovak uranium mines, addendum to the report for the Ministry of Health of CSR. UHP UP, Pribram-Kammenna, 1970.
27. Cech J. Contribution of non-radioactive carcinogens to occupational risk in some uranium mines. UHP UP, Jachymov, 1963.
28. Muller J. Lung cancer caused by ionizing radiation. Presented at the meeting on Epidemiological Studies in Human Radiobiology, Held 1965 December 13-17, Washington, D.C.: WHO.
29. Sevc J, Placek V. Lung cancer risk in relation to long-term exposure to radon daughter. In: *Proceedings of IRPA 2nd European Congress on Radiation Protection*, Budapest, 1972:29.
30. Sevc J, Placek V. Lung cancer in relation to long-term exposure to radon daughter products. Report of the partial task P09-335-053-02-01, IHE Praha - UHP UP Kamenna, 1972.
31. Sevc J, Placek V. Carcinogenic effects of radon daughter products. Final report of a study, IHE Praha, UHP UP Pribram - Kamenna, 1975.
32. Rericha V, Snajberg J, Reisenauer R, Ruzicka L. Monitoring the incidence of bronchogenic lung cancer and its dependence on the length of exposure in uranium miners in Jachymov and Horni Slavkov mines. In: *Compilation of scientific and specialized papers*. ZUNZ UP, Pribram: ZUNZ UP, 1966;4:21-31.
33. Swent L. Written communication. Prague, Czechoslovakia, (May 29, 1984).
34. Muller J, Wheeler WC, Gentleman JF, Suranyi G, Kusiak PA. Study of mortality of Ontario miners, 1955-1977, Part I. Ontario Ministry of Labor, May 1983.
35. Utting RE. Assessment of gamma doses absorbed by underground miners in Canadian uranium mines. In: Gomez M, ed. *Radiation hazards in mining*, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1981:533-538.
36. Phillips CR, Lueng H. Working level measurement of radon daughters and thoron daughters by personal dosimetry and continuous monitoring. In: M. Gomez, ed. *Radiation hazards in mining*. 1981;865-876.
37. Cote P and Townsend MG. Mixtures of radon and thoron daughters in underground atmospheres. *Health Phys* 1981;40:5-17.

38. Advisory Committee on Radiology Protection--Subcommittee on Risk Estimates. Risk estimates for exposure to alpha emitters. Ottawa: INFO-0090, 1982:14.
39. Muller J, et al. The Ontario miners mortality study. In: Gomez M, ed. Radiation hazards in mining, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1981: 359-362.
40. Morrison HI, Wigle DT, Stocker H, deVilliers AJ. Lung cancer mortality and radiation exposure among the Newfoundland fluorspar miners, pp. 372-376. In: M. Gomez, ed. Radiation hazards in mining, Am Institute of Mining, Metallurgical, and Petroleum Engineers Inc., New York, 1981.
41. Parsons WD, deVilliers AJ, Bartlett LS, Becklake MR. Lung cancer in a fluorspar mining community. II Prevalence of respiratory symptoms and disability. Brit J Industr Med 1964;21:110-116.
42. Axelson O, Sundell L. Mining, lung cancer, and smoking. Scand J Work Environ Health 1978;4:46-52.
43. Jorgensen HS. A study of mortality from lung cancer among (iron ore) miners in Kituna 1950-1970. Work Env Health 1973;10:126-133.
44. Damber L, Larsson L-G. Combined effects of mining and smoking in the causation of lung carcinoma: A case-control study in northern Sweden. Acta Radiol Oncology 1982; 21:305-313.
45. Boyd JT, Doll R, Faulds JS, Leiper, JP. Cancer of the lung in iron ore (haematite) miners. Br J Ind Med 1970;27:97-105.
46. Duggan MF, Soilleux PJ, Strong JC, Howell DM. The exposure of United Kingdom miners to radon. Br J Ind Med 1970;27:106-109.
47. Tirmarche M, Brenot J, Piechowski J, Chameaud J, Pradel J. The present state of an epidemiological study of uranium miners in France. In: Stocker H, ed. Proceedings of the International Conference (in two volumes) Vol I: Occupational radiation safety in mining. Toronto: Canadian Nuclear Association, 1985:344-349.
48. Jingyuan Z, Xiehua W, Xinhui H, et al. [Investigation of the radioactive aetiological factors of lung cancer among miners.] Zhongguo jixue kexueyuan xuebao 1981;3:127-131 (Chi.).
49. Wang X, Huang X, Huang S, et al. [Radon and miners lung cancer.] Zhonghua Fanjshe Yixue YU Fanjhu Zazhi 1984;4:10-14.
50. Editorial Committee for the Atlas of Cancer Mortality. Atlas of Cancer Mortality in the People's Republic of China, (1973-1975), China Map Press, 1st ed., 1978.
51. Edling C. Lung cancer and smoking in a group of iron ore miners. Am J Ind Med 1982;3:191-199.

52. Hornung RW. Comments regarding radon-smoking relationship as reported in Swedish iron miners. [Memorandum to Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer from Division of Surveillance, Hazard Evaluations and Field Studies, Statistical Services Section, Statistical Services Branch, April 3, 1985].
53. Criteria for a recommended standard...occupational exposure to chromium (VI). Cincinnati: U.S. Department of Health, Education and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, 1975; DHEW (NIOSH) publication no. 76-129.
54. Criteria for a recommended standard...occupational exposure to inorganic nickel. Cincinnati: U.S. Department of Health, Education and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, 1975; DHEW (NIOSH) publication no. 77-164.
55. Stokinger HE. A review of world literature finds iron oxides noncarcinogenic. *Am Ind Hyg Assoc J.* 1984;45:127-133.
56. Rutstein DD, Mullan RJ, Frazier TM, et al. Sentinel health events (occupational): A basis for physician recognition and public health surveillance. *Am J Public Health* 1983;73:1054-1062.
57. Duggan MJ. Some aspects of the hazard from airborne thoron and its daughter products. *Health Physics Pergamon Press* 1973;24:301-310.
58. American Thoracic Society. Evaluation of impairment/disability secondary to respiratory disease. *Am Rev Respir Dis* 1982;126:945-951.
59. American Thoracic Society. Surveillance for respiratory hazards in the occupational setting. *Am Rev Respir Dis* 1982;126:952-956.
60. American Thoracic Society. Screening for adult respiratory disease. *Am Rev Respir Dis* 1983;128:768-774.
61. Ferris BG. Epidemiology Standardization Project. *Am Rev Respir Dis* 1978;118:1-120.
62. Coles P, Morrison AS. Basic issues in population screening for cancer. *J Natl Can Inst* 1980;64:1263-1272.
63. Halperin WE, Ratcliffe JM, Frazier TM, et al. Medical screening in the workplace: Proposed principles. *J Occup Med* 1984.
64. Rothstein, MA. *Medical Screening of Workers.* Washington, DC: Bureau of National Affairs, 1984.

65. Handke JL, Stringer WT. Cytopathology in hard rock gold miners exposed to an asbestiform mineral--draft report. Cincinnati: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, 1984 [Unpublished Report].
66. Prorok PC, Mason TJ, Saccomano G, Archer VE. Relationships between duration of sputum cytologic states and carcinogenic exposures among uranium miners. In: Gomez M, ed. Radiation hazards in mining, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, 1981:359-362.
67. Ives JC, Buffler PA, Greenberg SD. Environmental associations and histological patterns of carcinoma of the lung: The challenge and dilemma in epidemiologic studies. *Am Rev Resp Dis* 1983;128:195-209.
68. Stayner LT and Wegman DH. Smoking, occupation, and histopathology of lung cancer: A case-control study with the use of the Third National Cancer Survey. *J Natl Cancer Inst* 1983;70:421-426.
69. Koop CE. Smoking and cancer. *Hospital Practice* 1984;19:107-132.
70. Laws PW, Rosenstein M. A somatic dose index for diagnostic radiology. *Health Physics* 1978;35:629-42.
71. Bernhard S, Pineau JF, Rannou A, Zettwoog P. 1983: One year of individual dosimetry in French mines. In: Stocker H, ed. Proceedings of the international conference (in two volumes) Vol II: Occupational radiation safety in mining. Toronto: Canadian Nuclear Association, 1985:526-540.
72. Viljoen J, and Balint AB. Comparing personal alpha dosimetry with the conventional area monitoring-time weighting methods of exposure estimation: A Canadian assessment. In: Stocker H, ed. Proceedings of the international conference (in two volumes) Vol. I: Occupational radiation safety in mining. Toronto: Canadian Nuclear Association, 1985:285-296.
73. Cooper WE. A comparison of radon-daughter exposures calculated for U.S. underground uranium miners based on MSHA and company records. In: M. Gomez, ed. Radiation hazards in mining. American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., New York, 1981;292-295.
74. Atomic Industrial Forum. Exposure of U.S. underground uranium miners to radon daughters in 1982 as reported by 29 underground uranium mine operations, from a survey made April 24, 1984. Submitted to MSHA.
75. National Emissions Standards for Hazardous Air Pollutants--standard for radon-222 emissions from underground uranium mines. Environmental Protection Agency. 40 CFR Part 61, 1985.

76. Bloomster CH, Enderlin WI, Young JK, Dirks JA. Cost survey for radon daughter control by ventilation and other control techniques. Battelle Pacific Northwest Laboratories. Draft April, 1984.
77. Annals of the International Commission on Radiological Protection: Limits for inhalation of radon daughters by workers. ICRP Publication 32. Pergamon Press, New York, 1981;26
78. Memorandum to Department of Health and Human Services, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Division of Standards Development and Technology Transfer from National Institutes of Health, National Toxicology Program, August 7, 1984.
79. World Health Organization. The evaluation of the carcinogenic risk of chemicals to humans. IARC Monographs, 1979;Supplement 1.
80. Code of Federal Regulations. U.S. Department of Labor. Occupational Safety and Health Administration. 29 CFR 1910.103, 1982.
81. O'Riordan MC, Rae S and Thomas GH. Radon in British mines - a review. In: M. Gomez, ed. Radiation Hazards in Mining, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., 1981;74-81.
82. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): Ionizing radiation: sources and biological effects. New York, 1982.
83. Environmental Protection Agency (EPA): Radiological Impact Caused by Emissions of Radionuclides into Air in the United States. EPA Publication No. 520/7-79-006, 1979.
84. Environmental Protection Agency (EPA): Occupational Exposure to Ionizing Radiation in the United States: A Comprehensive Summary for the Year 1975. EPA Publication No. 520/4-80-001, 1980.
85. U.S. Department of Energy. Statistical data of the uranium industry GJO-100 (81) Grand Junction Office, Colorado, January 1, 1981.
86. U.S. Department of Energy. Statistical data of the uranium industry GJO-100 (82) Grand Junction, Colorado, 1982.
87. U.S. Department of Energy. Statistical data of the uranium industry. GJO-100 (83) Grand Junction, Colorado, 1982.
88. Mine Safety and Health Administration, Department of Labor. New and revised safety and health standards for radiation (radon daughter exposure). Federal Register, 1979;44(107):31908-31920.
89. Gomez M, ed. Radiation Hazards in Mining. New York: Society of Mining Engineers, 1981.

90. Alderman Jr. Occupational health and safety of workers in Saskatchewan uranium mines. In: M. Gomez, ed. Radiation Hazards in Mining. Am Institute of Mining, Metallurgical and Petroleum Engineering, Inc., New York, 1981:608-615.
91. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. New York, 1977.
92. Niewiadomski GE: The role of the Bureau of Mines in radiation hazards research. In: M. Gomez, ed. Radiation Hazards in Mining, American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., 1981;97-104.
93. Franklin JC. Control of radiation hazards in underground uranium mines. In: M. Gomez, ed. Radiation Hazards in Mining, American Institute of Mining, Metallurgical, and Petroleum Engineers Inc, New York, 1981:441-446.
94. Martz DE and Schiager KJ. Protection against radon progeny inhalation using filter type respirators. Health Phys 1969;17:219-228.
95. Snihs JO. Radiation protection in Swedish Mines. Special problems. In: M. Gomez, ed. Radiation Hazards in Mining, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., 1981;283-285.
96. Goble R, Hattis D, Ballew MA, Thurston D. Implementation of the occupational lead standard. CENTED, Clark Univ, Worcester, MA, 1983.
97. Parker DR. Written communication to NIOSH on uranium and nonuranium mines. U.S. Department of Labor, Mine Safety and Health Administration (August 3, 1984).
98. Monson RR. Occupational Epidemiology, CRC Press, Inc., Boca Raton, Florida, 219 pp, 1980.
99. Thomas DC, McNeill KG, Dougherty C. Estimates of lifetime lung cancer risks resulting from radon daughter exposure. Health Physics, [in press], 1985.

APPENDIX A

MINING INDUSTRY: CURRENT WORKFORCE AND TYPICAL RADIATION EXPOSURES

Many countries have limited records of their current mining industry work forces and the workers' radiation exposures. In some countries, like Czechoslovakia, there are no figures published about the number of uranium miners because uranium is a strategic metal. In other countries, especially the United States, many people work in the mines for short periods of time before moving on, making it difficult to keep records of work force and exposure.

The miners most heavily exposed to radiation are the underground uranium workers and nonuranium hard rock miners (i.e., gold, fluorspar, iron, zinc, lead, copper). Coal miners have relatively low exposures to radon progeny, approximately 0.12 WLM annually [81]. This appendix describes the current work force and typical radiation exposures in the mining industry, including both uranium and nonuranium miners, in the United States and elsewhere (Table A-1).

A. Current Work Force

1. Uranium Miners

a. Miners in the United States

The number of underground mine workers (including miners and service and support staff) dropped from approximately 5,037 in 1980 to 2,150 in 1982 (Table A-2). The number of underground miners, the group receiving the highest exposures, dropped from 2,760 to 1,275. This decrease was due to a recent fall in the price of uranium and reduced uranium demand. In the mines in the United States there are numerous temporary, short-term workers; in 1978, out of all employees who worked underground, only 46 percent worked 1,500 or more hours underground (i.e., full-time).

b. Miners Outside the United States

Czechoslovakia, China, France, Italy, Australia, Canada, and Argentina have underground uranium mines (see Table A-3) [82].

Canada had over 3,690 underground miners in 1978, France had about 1,500 uranium miners in 1979, and Argentina had less than 100 underground miners in 1980 [82]. (At this time, figures are not available for the number of underground uranium miners in the other countries.)

Table A-1. Number, type, and production capacity of selected uranium and nonuranium mining industries, United States, 1975, with comparative data on exposures to radon decay products^a

| Mining industry | Number and type ^{b,c} of mines | | Production (thousand short tons) | Concentration of alpha radiation (WL) | Output by mining method (%) |
|-----------------|---|-------------|----------------------------------|---------------------------------------|-----------------------------|
| | open-pit | underground | | | |
| Iron | 57 | 11 | 497,000 | 0.14-0.90 | Open (96) |
| Copper | 46 | 15 | 959,000 | 0.09-0.21 | Open (80) |
| Zinc | (b) | 36 | 11,400 | 0.07-1.40 | Underground (100) |
| Clay | 1,317 | (c) | 80,500 | 0.10-0.46 | Open (>90) |
| Limestone | 2,900 | (c) | 971,000 | 0.05-0.16 | Open (>90) |
| Fluorspar | 1 | 14 | 593 | 0.30-2.20 | Underground (>90) |
| Bauxite | 11 | 1 | 16,600 | 0.07-1.40 | Open (>90) |
| Uranium | 36 | 251 | 15,900 | mean = 0.10 | Underground (>50) |

^aData on underground exposure to radon decay products come from EPA publications #520/7-79-006 (1979) and #520/4-80-001 (1980) [83,84]. The uranium mining exposure data were taken from the results of a survey in 1975, 3,344 miners were employed that year. The available data on metal and nonmetal miners' exposures were not sufficiently detailed to permit estimation of weighted mean annual exposures. The mine production data were taken from a 1978 survey report by the Mine Enforcement and Safety Administration.

^bA small, undetermined number are open-pit mines.

^cA small, undetermined number are underground mines.

Table A-2. Employment in the U.S. uranium mining industries, 1980-82

| Year | Underground miners | Underground service and support | Open-pit miners | Open-pit service and support | Technical | Other | Supervisory | Total |
|------|-----------------------|---------------------------------------|--------------------|------------------------------------|-----------|--------------------|-------------|--------------------|
| 1980 | 2,760 | 2,277 | 2,007 | 1,407 | 827 | 1,408 ^a | 1,082 | 11,768 |
| 1981 | 2,121 | 1,397 | 1,117 | 740 | 574 | 788 | 736 | 7,473 |
| 1982 | 1,275 | 875 | 792 | 573 | 503 | 426 | 613 | 5,057 ^b |

^aIncludes 201 truckers and 371 employees involved in shaft sinking and construction.

^bMay lack as many as 140 contract truckers.

Taken from Statistical Data of the Uranium Industry, U.S. Department of Energy, Grand Junction Area Office, Colorado [85,86,87].

Table A-3. Concentrations of, and exposure to, radon daughters in uranium mines

| Country | Year | Average potential alpha energy concentration (WL) | Average annual potential alpha energy exposure (WLM) | No. of miners | No. of miners exceeding 4 WLM ^{a/} |
|---------------|---------------------|---|--|---------------|---|
| France | 1971 | 0.18 | --- | --- | --- |
| | 1972 | 0.17 | --- | --- | --- |
| | 1973 | 0.18 | --- | --- | --- |
| | 1974 | 0.13 | --- | --- | --- |
| | 1975 | 0.11 | --- | --- | --- |
| | 1976 | --- | --- | --- | --- |
| | 1977 | --- | --- | --- | --- |
| | 1978 | --- | 2.0 | 1,284 | Approx. 140 |
| | 1979 | --- | 1.4 | 1,503 | 51 |
| United States | 1975 | 0.71 | 5.68 | Approx. 5,000 | --- |
| | 1976 | 0.58 | 4.64 | Approx. 5,000 | --- |
| | 1977 | 0.51 | 4.08 | Approx. 5,000 | --- |
| Italy | 1975 | <1 | --- | --- | --- |
| Canada | 1978 | 1 Leaching | 0.38 | 630 | --- |
| | | 4 Underground | 0.74 | 3,690 | --- |
| | | 1 Open-pit | 0.41 | 276 | --- |
| | 1978 | --- | 0.72 | 4,535 | 9 |
| | 1979 | --- | 0.74 | 6,883 | 1 |
| Argentina | Underground 1977-79 | --- | 2.4 | 286-379 | --- |
| | | --- | 2.4 | 95 | 0 |
| | Open-pit 1980 | --- | 0.12 | 285 | 0 |

^aThe maximum permissible exposure in many countries.

^bData from the National Dose Registry in Canada.

--- = data not available

Taken from Ionizing Radiation: Sources and Biological Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, N.Y., 1982, p. 199 [82].

2. Nonuranium Miners

a. Miners in the United States

In 1984, MSHA reported that 23,721 miners (including 1,127 mining uranium) are employed full-time and 3,063 are employed part-time (includes 177 mining uranium) in metal and non metal underground mines in the United States. (Table A-4).

Most of these miners are probably exposed to negligible quantities of radon progeny, although there is insufficient data to prove this. MSHA requires that underground nonuranium mining companies record the individual exposures of all miners who work in areas where radon progeny levels exceed 0.3 WL [88]. Table A-5 lists all of the mines that submitted individual records of exposure to MSHA during 1979-1983, and the number of miners for whom records were submitted. Some mines submitted records for all of their employees, including workers who received no radon progeny exposures; for example, 90 percent of the Climax and Henderson mine exposures were essentially zero during 1983. These mines occasionally have readings above 0.3 WL and, thus, are required to keep exposure records, but an individual miner's annual average exposure may be less than 4 WLM.

During 1983, the mining companies were required to keep records on no more than 450 employees (Table A-5). The rest of the approximately 25,000 workers who mine in underground metal and non metal mines (excluding uranium) should receive even lower radon progeny exposures.

b. Miners Outside the United States

The figures for the number of hard rock miners are incomplete (see Table A-6). South Africa has a large number of hard rock miners, approximately 320,000, primarily employed in the gold mines. The most recent figures on the number of iron, zinc, lead, copper, or gold miners showed about 1,370 miners in Finland, 2,500 in Italy, 1,380 in Norway, 4,400 in Sweden, and 2,350 in Great Britain [82].

B. Current Exposures in Mining Industries

1. Uranium Miners

a. Miners in the United States

Most of the information on current underground uranium mining radiation exposure is reliant upon company records. There remains disagreement between the companies' records and the U.S. Mine Safety and Health Administration's (MSHA) inspection records [57]. The average annual cumulative exposure for all underground uranium mine workers is relatively low; members of the Atomic Industrial Forum (AIF) recorded an average exposure of 1.03 WLM in 1978 (see Tables A-7 through A-11). Because of the many temporary workers in the

Table A-4. Employment in United States metal and non metal underground mines
June 26, 1984

| Underground mines DESCRIPTION | Full-time personnel | | Intermittent/ Seasonal | | Total | |
|-------------------------------------|------------------------|-------------|---------------------------|-------------|--------------|-------------|
| | # operations | # employees | # operations | # employees | # operations | # employees |
| Iron ore | 1 | 303 | 0 | 0 | 1 | 303 |
| Copper ore | 11 | 2,316 | 11 | 171 | 22 | 2,487 |
| Lead/zinc | 22 | 3,093 | 13 | 229 | 35 | 3,322 |
| Gold-lode & PL | 29 | 2,080 | 181 | 994 | 210 | 3,074 |
| Silver ores | 24 | 1,990 | 58 | 357 | 82 | 2,347 |
| Cobalt | 0 | 0 | 1 | 3 | 1 | 3 |
| Molybdenum | 2 | 1,297 | 2 | 268 | 4 | 1,565 |
| Tungsten | 2 | 20 | 4 | 110 | 6 | 130 |
| Uran-vanad | 2 | 44 | 9 | 43 | 11 | 87 |
| Uranium | 23 | 1,127 | 25 | 177 | 48 | 1,304 |
| Metal ores | 1 | 8 | 0 | 0 | 1 | 8 |
| Antimony | 0 | 0 | 1 | 2 | 1 | 2 |
| Platinum GRP | 0 | 0 | 1 | 19 | 1 | 19 |
| Oil shale | 3 | 174 | 6 | 68 | 9 | 242 |
| Limestone-DM | 1 | 15 | 1 | 22 | 2 | 37 |
| Marble-DM | 1 | 29 | 0 | 0 | 1 | 29 |
| Slate (DM) | 1 | 5 | 0 | 0 | 1 | 5 |
| Limestone-CB | 75 | 1,789 | 28 | 358 | 103 | 2,147 |
| Marble (CB) | 7 | 88 | 0 | 0 | 7 | 88 |
| Sandst (CB) | 2 | 29 | 0 | 0 | 2 | 29 |
| Clay (Fire) | 5 | 74 | 1 | 3 | 6 | 77 |
| Clay (Comm) | 1 | 8 | 2 | 10 | 3 | 18 |
| Fluorspar | 3 | 63 | 1 | 3 | 4 | 66 |
| Pot, Soda & Bor | 1 | 397 | 0 | 0 | 1 | 397 |
| Boron mineral | 1 | 243 | 0 | 0 | 1 | 243 |
| Potash | 4 | 1,447 | 2 | 34 | 6 | 1,481 |
| Trona | 2 | 1,426 | 0 | 0 | 2 | 1,426 |
| Sodium comp | 3 | 1,804 | 0 | 0 | 3 | 1,804 |
| Phosphate RK | 1 | 117 | 0 | 0 | 1 | 117 |
| Salt rock | 13 | 1,947 | 1 | 142 | 14 | 2,089 |
| Gypsum | 9 | 371 | 1 | 12 | 10 | 383 |
| Talc-soap & py | 5 | 140 | 2 | 2 | 7 | 142 |
| Nonmetal min | 2 | 33 | 1 | 4 | 3 | 37 |
| Gemstones | 0 | 0 | 2 | 6 | 2 | 6 |
| Gilsonite | 12 | 69 | 5 | 23 | 17 | 92 |
| Perlite | 0 | 0 | 1 | 3 | 1 | 3 |
| Salt (evap) | 1 | 217 | 0 | 0 | 1 | 217 |
| Lime | 3 | 958 | 0 | 0 | 3 | 958 |
| Total | 273 | 23,721 | 360 | 3,063 | 633 | 26,784 |

Taken from the Mine Safety and Health Administration, June 26, 1984.

Table A-5. Nonuranium mines that submitted individual radiation exposure records to MSHA, 1979-1983

| Mine and company name | Recorded number of employees | | | | |
|--|------------------------------|-------|-------|-------|-------|
| | 1979 | 1980 | 1981 | 1982 | 1983 |
| Climax Molybdenum* Amax | 3,196 | 2,264 | 1,747 | 1,889 | 1,915 |
| Warm Springs Phosphate Cominco American | 24 | 22 | 22 | 23 | 23 |
| Crowell Fluorspar J. I. Crowell | 10 | --- | --- | --- | --- |
| Pine Creek Tungsten Union Carbide | 299 | 319 | 260 | --- | 89 |
| Henderson Molybdenum* Amax | --- | 1,534 | 876 | 1,429 | 1,462 |
| Emperius Chevron | --- | 13 | 15 | --- | --- |
| Bulldog Mt. Project Homestake | --- | 147 | --- | --- | --- |
| Ontario Noranda | --- | --- | 232 | --- | --- |
| Stanley Equity Gold Inc. | --- | --- | 11 | --- | --- |
| Leadville Unit Asarco | --- | --- | --- | 95 | --- |
| Revenue - Virginius Ranchers | --- | --- | --- | 7 | --- |
| TOTAL | 3,529 | 4,299 | 3,163 | 3,443 | 3,489 |

*Climax and Henderson mine exposures ran about 90 percent zeros in 1983.
 --- = no data submitted

Taken from the Mine Safety and Health Administration, August 3, 1984 [97].

Table A-6. Concentrations of, and exposure to, radon daughters in nonuranium mines^a

| Country | Year | Average potential alpha energy concentrations (WL) | Annual potential alpha energy exposure (WLM) | No. of miners /mines | No. of miners exceeding 4 WLM |
|-----------------|-----------|--|--|----------------------|-------------------------------|
| Finland | 1972-1974 | 0.2-0.4 | --- | 1,300/23 | --- |
| | 1975-1977 | --- | 0.38 | 1,370/16 | 0 |
| Italy | 1975 | 0.01-0.6 | --- | 2,500/16 | Approx. 75 |
| Norway | 1972 | 0.07 | 0.64 | 1,870/33 | --- |
| | 1980 | 0.05 | 0.45 | 1,380/23 | --- |
| Poland | 1970 | | | | |
| Copper | | 1-2 | --- | --- | --- |
| Iron | | 1 | --- | --- | --- |
| Pyrite | | 4 | --- | --- | --- |
| Phosphate | | 0.8 | --- | --- | --- |
| Zinc and lead | | 0.9 | --- | --- | --- |
| Baryte | | 0.2 | --- | --- | --- |
| Coal | | 0.1 | --- | --- | --- |
| South Africa | 1973 | --- | 1.7 | 320,000 | --- |
| Sweden | 1970 | --- | 4.8 | 4,800/5 | 2000 |
| | 1974 | --- | 2.1 | 4,600/50 | 360 |
| | 1975 | --- | 1.9 | 5,300/45 | 270 |
| | 1976 | --- | 1.7 | 5,300/46 | 225 |
| | 1977 | --- | 1.6 | 5,200/45 | 475 |
| | 1978 | --- | 0.9 | 5,300/47 | 270 |
| | 1979 | --- | 0.7 | 4,400/35 | 0 |
| | 1980 | --- | 0.7 | 4,400/35 | 0 |
| United Kingdom | 1968 | 0.01 ^b | --- | 220,000/420 | --- |
| | 1976 | --- | 2-3 ^c | 2,000/80 | 560 |
| National coal | 1981 | --- | 0.12 | 185,200 | --- |
| Private coal | 1981 | --- | 0.24 | 1,500 | --- |
| Other than coal | 1981 | --- | 2.60 | 2,346/108 | 94 |
| United States | 1975 | 0.31 | --- | --- | --- |
| | 1976 | 0.22 | --- | --- | --- |
| | 1977 | 0.12 | --- | /163 | --- |

^aIf not otherwise noted, the mines are iron, zinc, lead, copper, or gold mines.

^bThis value is called "typical" for large nationalized coal mines.

^cBased on measurements in about 80 percent of all noncoal mines.

--- = data not available

From Ionizing Radiation: Sources and Biological Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, N.Y., 1982, p. 198 [82].

Table A-7. Average exposures (WLM) during 1978 to United States uranium miners

| Job category | All | | Full time | |
|-----------------|--------------|-------------|------------|-------------|
| | Number | av WLM | Number | av WLM |
| Production | 3,967 | 1.20 | 1,744 | 1.74 |
| Maintenance | 763 | 0.85 | 471 | 0.97 |
| Service | 1,759 | 0.81 | 626 | 1.14 |
| <u>Salaried</u> | <u>1,015</u> | <u>0.97</u> | <u>585</u> | <u>1.10</u> |
| Total | 7,504 | 1.03 | 3,426 | 1.45 |

*The first two columns refer to all miners who worked underground during the year and the last two refer to those who worked underground at least 1,500 hours.

Taken from Radon Daughter Exposure to Uranium Miners by B.L. Cohen, pp. 286-291, In: Radiation Hazards in Mining, M. Gomez, ed. 1981 [89].

Table A-8. United States uranium miner exposures

| Total employment | Average exposure | Miners having exposure in indicated intervals, percentage | | | | |
|------------------|------------------|---|---------|---------|---------|-------|
| | | 0-1 WLM | 1-2 WLM | 2-3 WL, | 3-4 WLM | 4 WLM |
| 3,344 | 1.07 WLM | 56.5 | 23.5 | 12.4 | 6.1 | 1.4 |

From Occupational Exposure to Ionizing Radiation in the United States: A Comprehensive Summary for the Year 1975 by J.R. Cook and D.R. Nelson, EPA #520/4-80-001, November 1980, p. D-12 [84].

Table A-9. Cumulative frequency distribution of annual exposures to radon progeny of persons who worked underground 1,500 hours or more^a, United States uranium miners

| Annual Exposure | Cumulative percentage by years | | | | | | | 7-year Average |
|-----------------|--------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|----------------|
| | 1973 (N=699) ^b | 1974 (N=1,216) | 1975 (N=1,587) | 1976 (N=2,052) | 1977 (N=3,158) | 1978 (N=3,426) | 1979 (N=3,421) | |
| ≤1.0 WLM | 39.5 | 33.8 | 46.6 | 41.9 | 44.1 | 41.8 | 37.5 | 40.7 |
| ≤2.0 WLM | 68.5 | 65.5 | 75.5 | 68.7 | 72.0 | 74.5 | 69.6 | 70.6 |
| ≤3.0 WLM | 88.7 | 88.4 | 91.4 | 89.1 | 92.7 | 92.1 | 91.5 | 90.6 |
| ≤4.0 WLM | 99.0 | 98.5 | 98.9 | 99.8 | 99.9 | 99.1 | 99.8 | 99.3 |
| ≤5.0 WLM | 100.0 | 99.9 | 99.6 | 99.9 | 100.0 | 99.6 | 100.0 | 99.9 |
| ≤6.0 WLM | - | 100.0 | 100.0 | 100.0 | - | 98.8 | - | - |

^aData provided by L.W. Swent (1981). Since this tabulation includes only those employees who worked underground 1,500 hours or more, duplications are unlikely.

^bN is the number of employees included in the report; the number of underground uranium mine operators providing data ranged from 32 in 1974 and 1975 to 71 in 1979.

From Radiation Monitoring Priorities for Uranium Miners by K.J. Schiager and J.A. Johnson, p. 738-745, In: Radiation Hazard in Mining, M. Gomez, ed. 1981 [89].

Table A-10. Exposure of United States underground uranium miners to radon daughters in 1979 as reported by 71 underground uranium mine operations, for all persons assigned to work underground in 1979^{a,b}

| All persons assigned to work underground in 1979 | | | | | | | | |
|--|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|
| | 0-1.0 WLM | 1.01-2.0 WLM | 2.01-3.0 WLM | 3.01-4.0 WLM | 4.01-5.0 WLM | 5.01-6.0 WLM | Over 6.0 WLM | Total |
| Production ^c - No. Persons | 2,938 | 1,082 | 621 | 247 | 3 | 0 | 0 | 4,891 |
| - % | 60.0 | 22.1 | 12.7 | 5.1 | 0.1 | 0.0 | 0.0 | 100.0 |
| Maintenance ^d - No. Persons | 994 | 187 | 53 | 20 | 3 | 0 | 0 | 1,257 |
| - % | 79.1 | 14.9 | 4.2 | 1.6 | 0.2 | 0.0 | 0.0 | 100.0 |
| Service ^e - No. Persons | 1,651 | 330 | 128 | 27 | 0 | 0 | 0 | 2,136 |
| - % | 77.3 | 15.4 | 6.0 | 1.3 | 0.0 | 0.0 | 0.0 | 100.0 |
| Salaried ^f - No. Persons | 1,032 | 284 | 98 | 8 | 0 | 0 | 0 | 1,422 |
| - % | 72.5 | 20.0 | 6.9 | 0.6 | 0.0 | 0.0 | 0.0 | 100.0 |
| Total - No. Persons | 6,615 | 1,883 | 900 | 302 | 6 | 0 | 0 | 9,706 |
| - % | 68.1 | 19.4 | 9.3 | 3.1 | 0.1 | 0.0 | 0.0 | 100.0 |

^aThere is a possibility that persons may have worked for more than one operator in 1979 and, therefore, have been reported more than once in the above tabulation. The January 1, 1980 issue of "Statistical Data of the Uranium Industry" of the Grand Junction office of the U.S. Department of Energy shows average employment in U.S. underground uranium mines in 1979 to be 5,706 persons. The DOE figures, however, do not include technical or supervisory persons who work underground.

^bExposures reported in this survey are based on more than 130,000 determinations of radon daughter concentrations.

^cProduction includes production and development miners.

^dMaintenance includes mechanics and electricians.

^eService includes motormen, haulage crews, drift repairmen, station tenders, skip tenders, etc.

^fSalaried includes engineers, supervisors, geologists and ventilation personnel.

In mines where production employees also perform maintenance, service and supervisory duties., such employees were classified as production workers.

Taken from A Comparison of Radon Daughter Exposures Calculated for U.S. Underground Uranium Miners Based on MSHA and Company Records by W.E. Cooper, pp. 292-295, In: Radiation Hazards in Mining, M. Gomez, ed. 1981 [89].

Table A-11. Exposure of U.S. underground uranium miners to radon daughters in 1979 as reported by 71 underground uranium mine operations, for persons who worked underground 1,500 hours or more in 1979^{a,b}

| | | Persons who worked underground 1500 hours or more in 1979 | | | | | | | Total |
|--------------------------|--------------|---|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|
| | | 0-1.0 WLM | 1.01-2.0 WLM | 2.01-3.0 WLM | 3.01-4.0 WLM | 4.01-5.0 WLM | 5.01-6.0 WLM | Over 6.0 WLM | |
| Production ^c | -No. Persons | 348 | 609 | 517 | 234 | 3 | 0 | 0 | 1,711 |
| | - % | 20.3 | 35.6 | 30.2 | 13.7 | 0.2 | 0.0 | 0.0 | 100.0 |
| Maintenance ^d | -No. Persons | 283 | 135 | 46 | 21 | 3 | 0 | 0 | 488 |
| | - % | 58.0 | 27.7 | 9.4 | 4.3 | 0.6 | 0.0 | 0.0 | 100.0 |
| Service ^e | -No. Persons | 401 | 182 | 112 | 23 | 0 | 0 | 0 | 718 |
| | - % | 55.9 | 25.3 | 15.6 | 3.2 | 0.0 | 0.0 | 0.0 | 100.0 |
| Salaried ^f | -No. Persons | 253 | 171 | 75 | 5 | 0 | 0 | 0 | 504 |
| | - % | 50.2 | 33.9 | 14.9 | 1.0 | 0.0 | 0.0 | 0.0 | 100.0 |
| Total | -No. Persons | 1,285 | 1,097 | 750 | 283 | 6 | 0 | 0 | 3,421 |
| | - % | 37.5 | 32.1 | 21.9 | 8.3 | 0.2 | 0.0 | 0.0 | 100.0 |

^aNo duplications of employees are possible in this tabulation because no employee was counted who worked underground less than 1,500 hours (75 percent of a normal year of about 2,000 hours).

^bOperators that reported their data for inclusion in this survey are: The Anaconda Company, Atlas Minerals, Cobb Nuclear Corporation, Cotter Corporation, Exxon Minerals Company, U.S.A., Gulf Mineral Resources Company, Kerr-McGee Corporation, M&M Mining Company, Pathfinder Mines Corporation, Ranchers Exploration and Development Corporation, Ray Williams Mining Company, Reserve Oil & Minerals Corporation, Rio Algom Corporation, Sohio Natural Resources Company, Todilto Exploration & Development Corporation, Union Carbide Corporation, United Nuclear Corporation, United Nuclear-Homestake Partners, and Western Nuclear, Inc. The Colorado Bureau of Mines furnished the data for 45 small operators in Colorado. In cases where corporations had widely separated operations under different managers, each was considered a separate operation.

^cProduction includes production and development miners. In mines where production employees also perform maintenance, service and supervisory duties, such employees were classified as production workers.

^dMaintenance includes mechanics and electricians.

^eService includes motormen, haulage crews, drift repairmen, station tenders, skip tenders, etc.

^fSalaried includes engineers, supervisors, geologists and ventilation personnel.

Taken from A Comparison of Radon Daughter Exposures Calculated for U.S. Underground Uranium Miners Based on MSHA and Company Records by W.E. Cooper, pp. 292-295, In: Radiation Hazards in Mining, M. Gomez, ed. 1981 [89].

uranium mines in the United States, this figure is somewhat misleading. These workers can receive high exposures, and because they only work for short periods of time, their annual average exposure is low. The average exposure for those miners working full time, that is over 1,500 hours underground, was higher; 1.45 WLM in 1978.

Underground mining exposure records were placed into four general job categories by the AIF, i.e., production, maintenance, service, and salaried. As a group, the production workers who worked more than 1,500 hours underground should have higher exposures than the remaining uranium mining work force. In 1978, the average exposure of these workers was 1.74 WLM (see Table A-7) and in 1979 their average exposure was approximately 1.88 WLM [57]. In contrast, in 1979 and 1980, MSHA inspectors recorded average radon progeny WL concentrations for underground uranium mining production workers of 0.30 WL or higher, which means that some of these workers could receive 4 WLM or more per year. Cooper estimated that the average annual exposure of full-time underground production workers was about 2.9 WLM during 1979 [57]. The number of workers that receive these high exposure levels may be small; AIF reported that among full-time underground uranium miners in 1979, only 3 out of 1,711 production workers and 3 out of 488 maintenance workers received more than 4 WLM annually (see Tables A-10 and A-11).

Overall, most uranium mine workers' (including those workers who spend only part of their time underground) exposure is well below the standard of 4 WLM and on the average may be about 1 WLM [82], (see Table A-7). A relatively small number of workers, primarily full-time underground production and maintenance workers, have exposures above the 4 WLM standard (see Tables A-9 through A-11). The most recent available data, for 1982, showed that only 2 underground employees (0.1 percent) received radon progeny exposures of 4.0-5.0 WLM and 44 employees (1.6 percent) received exposures of 3.0-4.0 WLM. [58]. It should be possible to lower radon progeny exposure levels for this relatively small number of miners.

b. Miners Outside the United States

The exposure of underground uranium miners depends on the quality of the uranium ore body and the ventilation rate. In other countries, (excepting Canada) the uranium ore is frequently of a lower grade than the ore in the United States, so with good ventilation techniques, the foreign uranium miners should receive lower exposures than the miners in the United States. Recent figures for radiation exposure in underground uranium mines in Canada, France, India, Argentina, and China have been published in the literature (see Table A-3) [82].

The underground uranium miners of Canada had an average annual exposure to radon progeny of 0.74 WLM in 1978. In 1980, the median exposure for miners in three underground mines in Saskatchewan was below 0.6 WLM and only about three workers in one mine were exposed

to 3-4 WLM. In addition, some of these miners had substantial gamma exposure. In the Cluff mine, gamma exposures were as high as 3.5 rem and above, and in the Eldorado and Cluff mines many workers (approximately 60) were exposed to 1-3 rem [90].

The French uranium miners had average annual radon progeny exposures of 2.0 WLM and 1.4 WLM in 1978 and 1979, respectively [82]. In 1975, the median radon progeny exposure was below 0.10 WL, yet as many as 5.35 percent of the workers were exposed to 0.30 to 0.80 WL, potentially receiving more than 4 WLM annually (see Table A-12) [91]. In 1975, there was also a record of gamma exposure in French underground uranium mines. The mean annual dose was 0.49 rem, but some miners received much higher doses; 9.16 percent received 1.0-1.5 rem, 5.3 percent received 1.5-2.5 rem and 0.65 percent received 2.5-3.0 rem [91]. In the underground uranium mines in France, gamma exposure may constitute a major part of the total radiation.

There is limited information available concerning typical radon progeny exposures in underground uranium mines in India, Argentina, and China [82]. For the mines in India, figures for potential exposure are given by job category. In 1979, the drilling crew received an estimate of 2.6 WLM of potential alpha energy exposure, the mucking crew about 2.1 WLM, and "others" about 1.7 WLM (see Table A-13) [82]. In Argentina, the average annual radon progeny exposure was about 2.4 WLM during 1980.

2. Nonuranium Miners

a. Hard Rock Miners in the United States

Some of the highest radon progeny exposures are found in the iron, zinc, fluorspar, and bauxite mines (Table A-1). In 1975, iron miners were exposed to 0.14-0.90 WL, zinc miners to 0.07-1.40 WL, fluorspar miners to 0.30-2.20 WL and bauxite miners to 0.07-1.40 WL [83,84]. If these readings are typical, some hard rock miners in the United States, especially those in fluorspar mines, could have radon progeny exposures much higher than 4 WLM.

However, recent data submitted by U.S. metal and non metal mining companies to MSHA suggests that no more than 450 individuals are occasionally exposed to 0.3 WL (Table A-5). During 1983, only 4 companies, 2 molybdenum, 1 phosphate and 1 tungsten, submitted individual exposure records for their employees to MSHA. It is possible that the mining companies failed to report additional employees who received radon exposures, but this is the only data available. From this data, one concludes that, except for a few molybdenum, phosphate, and tungsten mines, radon progeny exposure is not a problem in U.S. hard rock mines. Thus, in general, hard rock mines should be able to meet an annual radon progeny standard below 4 WLM.

Table A-12. Frequency distribution of radon exposures among French uranium miners (underground workers), 1971-1975

| Year | Exposure range (fraction of MAC) ^a | | | | | | | | | Mean Annual Exposure (WL) |
|------|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-------|---------------------------|
| | <0.10 | 0.11-0.20 | 0.21-0.30 | 0.31-0.40 | 0.41-0.50 | 0.51-0.60 | 0.61-0.80 | 0.81-1.00 | >1.00 | |
| | Percentage of workers | | | | | | | | | |
| 1971 | 36.08 | 22.39 | 19.90 | 13.12 | 6.22 | 2.14 | 0.15 | --- | --- | 0.18 |
| 1972 | 37.30 | 22.55 | 21.13 | 12.27 | 4.36 | 2.24 | 0.15 | --- | --- | 0.17 |
| 1973 | 37.70 | 19.32 | 19.43 | 14.40 | 7.72 | 1.43 | --- | --- | --- | 0.18 |
| 1974 | 43.38 | 26.89 | 21.46 | 6.21 | 1.35 | 0.71 | --- | --- | --- | 0.13 |
| 1975 | 53.91 | 24.71 | 16.03 | 4.58 | 0.66 | 0.11 | --- | --- | --- | 0.11 |

^aFor each worker the annual exposure is represented by the mean annual air concentration and is expressed as a fraction of the maximum annual concentration (MAC). Given the administrative arrangements and the effective state of equilibrium between radon and its daughters, the MAC is practically equivalent to 1 WL.

Taken from Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, N.Y., p. 267, 1977 [91].

Table A-13. Estimated potential alpha energy exposure of different categories of mine workers in the Jadugkda underground mines, India

| Year | Estimated potential alpha energy exposure (WLM) | | |
|------|---|--------------|-----------|
| | Drilling crew | Mucking crew | Others |
| 1965 | 4.9 ± 2.6 | 2.1 ± 1.0 | 1.7 ± 1.0 |
| 1966 | 2.3 ± 1.2 | 3.5 ± 1.8 | 1.2 ± 0.9 |
| 1967 | 2.0 ± 1.1 | 5.2 ± 2.7 | 1.6 ± 1.1 |
| 1968 | 3.8 ± 2.0 | 3.2 ± 1.6 | 2.3 ± 1.5 |
| 1969 | 4.1 ± 2.2 | 6.5 ± 3.4 | 2.4 ± 1.7 |
| 1970 | 2.1 ± 1.1 | 3.0 ± 1.4 | 0.7 ± 0.5 |
| 1971 | 1.7 ± 0.9 | 2.0 ± 1.1 | 1.1 ± 0.8 |
| 1972 | 0.7 ± 0.6 | 1.6 ± 1.4 | 1.4 ± 1.3 |
| 1973 | 0.6 ± 0.3 | 0.6 ± 0.3 | 0.7 ± 0.5 |
| 1974 | 1.6 ± 0.6 | 5.5 ± 5.0 | 2.0 ± 1.6 |
| 1975 | 2.2 ± 0.7 | 2.3 ± 1.9 | 3.5 ± 1.7 |
| 1976 | 5.5 ± 4.4 | 2.5 ± 1.1 | 0.7 ± 0.1 |
| 1977 | 1.6 ± 0.6 | 1.7 ± 0.7 | 1.4 ± 0.7 |
| 1978 | 0.8 ± 0.2 | 1.4 ± 0.7 | --- |
| 1979 | 2.6 ± 1.0 | 2.1 ± 0.6 | 1.7 ± 0.3 |

--- data not available

Taken from Ionizing Radiation: Sources and Biological Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, N.Y., 1982, p. 199 [82].

b. Hard Rock Miners Outside the United States

Radon progeny exposure levels have been measured in nonuranium mines in Finland, Italy, Norway, South Africa, Sweden, the United Kingdom and Poland (Tables A-14 to A-16) [82,81]. The most recent figures for all of these countries show annual average radon progeny exposures of 2.6 WLM or less. However, in many of these countries the average potential alpha energy concentrations exceed 0.3 WL, suggesting that individual miners may be exposed to more than 4 WLM per year (if they work full time during the year). Nonuranium miners (especially iron, zinc, lead, copper, or gold miners) in Italy, Poland, South Africa, and Great Britain may be exposed to more than 4 WLM annually [82]. In the United Kingdom, 4 percent of the noncoal miners were exposed to 4 WLM or more, however, many of the miners did not work full 8-hour shifts. If the underground noncoal miners in the United Kingdom worked full 8-hour shifts, as many as 20 percent of the workers could be exposed above 4 WLM/yr [81]. Recent reports for five Chinese tin mines showed radon progeny levels of 0.67 to 1.73 WL during 1978 [40].

Table A-14. Distribution of radon-daughter exposure in nonuranium mines in various countries

| Country | | Year | Radon-daughter concentration range (WL) | | | | ALL | Weighted average annual exposure ^a (WLM) |
|---|--------|------|---|------------|-----------|----------|---------|---|
| | | | <0.1 | 0.1-0.3 | 0.3-1.0 | >1.0 | | |
| (Number and, in parentheses, percentage of miners or mines) | | | | | | | | |
| Finland | Miners | 1973 | 469(35) | 246(18) | 247(19) | 369(28) | 1,331 | 8.8 |
| | | 1974 | 898(68) | 310(23) | 119(9) | 0 | 1,327 | 1.7 |
| | Mines | 1973 | 8(36) | 4(18) | 4(18) | 6(28) | 22 | --- |
| | | 1974 | 13(65) | 5(25) | 2(10) | 0 | 20 | --- |
| Italy | Mines | 1973 | 8(50) | 4(25) | 4(25) | 0 | 16 | --- |
| Norway | Miners | 1972 | 1,608(86) | 264(14) | 0 | 0 | 1,872 | 0.9 |
| | Mines | 1972 | 20(83) | 4(17) | 0 | 0 | 24 | --- |
| South Africa | Miners | 1973 | 227,000(71) | 69,000(21) | 21,000(7) | 3,000(1) | 320,000 | 1.7 |
| Sweden | Miners | 1970 | 1,110(22) | 1,560(33) | 2,000(42) | 130(3) | 4,800 | 4.8 |
| | | 1974 | 1,860(40) | 2,390(52) | 360(8) | 0 | 4,610 | 2.1 |
| | | 1976 | 2,730(51) | 2,345(44) | 225(4) | 0 | 5,300 | 1.7 |
| | Mines | 1970 | 25(45) | 8(15) | 18(33) | 4(7) | 55 | --- |
| | | 1974 | 28(56) | 14(28) | 8(16) | 0 | 50 | --- |
| | | 1976 | 29(63) | 12(26) | 5(11) | 0 | 46 | --- |
| United Kingdom | Miners | 1973 | 1,073(60) | 49(3) | 223(12) | 443(25) | 1,788 | 4.2 |
| | | 1975 | | | | | | 3.4 |
| | Mines | 1973 | 25(61) | 3(7) | 9(22) | 4(10) | 41 | |

^aThe weighted annual average exposures are calculated by multiplying the number of miners in each group by the mean values of the radon concentration (0.05, 0.2, 0.65 or 2 WL) and by 12 months, obtaining the sum of the products and dividing by the total number of miners. The United Kingdom miners represent 70 percent of all noncoal miners and the United Kingdom mines represent 41 percent of all noncoal mines.

Taken from Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, N.Y., p. 254, 1977 [91].

Table A-15. Employment and exposure in British mines

| Type of mine | Miners employed underground | WLM in a year | Collective Exposure man WLM/y | |
|-----------------|-----------------------------|---------------|-------------------------------|-----------------|
| National coal | 185,200 | 0.12 | --- | |
| Private coal | 1,500 | 0.24 | 2.26 | 10 ⁴ |
| Other than coal | 2,346 | 2.60 | 6.10 | 10 ³ |

Table A-16. Weighted exposures* of noncoal miners in 1981 and 1976

| Exposure WLM in a year | Number of men exposed in year | | % of men exposed in year | |
|------------------------|-------------------------------|-------|--------------------------|------|
| | 1981 | 1976 | 1981 | 1976 |
| 0 to 1 | 938 | 986 | 40 | 49 |
| 1 to 4 | 1,314 | 454 | 56 | 23 |
| 4 and more | 94 | 564 | 4 | 28 |
| All | 2,346 | 2,004 | 100 | 100 |

*Time-weighted full-shift exposures

Tables A-15 and A-16 from Radon in British Mines - a review by M.C. O'Riordan, S. Rae and G.H. Thomas, pp. 74-81, In: Radiation Hazards in Mining, M. Gomez, ed. 1981 [89].

APPENDIX B

CURRENT METHODS OF REGULATION AND CONTROL OF RADIATION EXPOSURES IN UNDERGROUND MINES

A. Engineering Controls

Table B-1 lists information about mining radiation control methods, including ventilation, sealants, bulkheads, backfilling, wet drilling, air cleaning, and separate air supplies. It may be most effective to combine some of these techniques, e.g., to use positive pressure ventilation in combination with procedures to decrease the volume of the mine air needing ventilation, such as bulkheads or backfilling. Bulkheads could be made more secure against radon gas leaks by maintaining a slight negative pressure behind the bulkhead and painting sealant on nearby exposed rock. Finally, most of the techniques described in Table B-1 and in this chapter will decrease inhalation exposure to alpha radiation from the decay products of radon and thoron gases, but won't affect gamma radiation levels.

1. Mechanical Ventilation

Mechanical ventilation is the primary and most successful technique currently in use for reducing exposure to radon decay products. In uranium mines in the United States, during the early 1950's before mechanical ventilation became prevalent, average measurements of 2-200 WL of radon decay products were common [11]. In contrast, during 1979 and 1980, the highest average working level for radon progeny recorded by MSHA was 0.46 WL (Table B-2). Thus, there has been a great decrease in exposure to radon decay products in uranium mines primarily due to improvement in ventilation. Sweden has also successfully reduced radon progeny levels in nonuranium mines with mechanical ventilation. The average annual exposure for the nonuranium miners of Sweden was 4.7 WLM in 1970, due to ventilation improvements, and decreased to 0.7 WLM in 1980 [95]. In the case of uranium miners in the United States, it is not clear whether there could be significant further decreases in exposures to radon decay products with ventilation improvements alone. These few mines may need to use other techniques, besides dilution ventilation, to reduce miners' exposure to radon progeny (Table B-1).

2. Other Dust Control Methods

Spraying water and delaying blasting until the end of shifts are two other dust control methods currently in use in most underground uranium mines. Most mines use these methods to control silica dust, but in uranium mines these methods can help control uranium ore dust.

Drilling and blasting are two mining activities that generate high levels of uranium ore dust. Exposure to uranium ore dust alone may be carcinogenic, and high dust or smoke levels may modify the respiratory tract distribution of a miner's exposure to radon progeny (by increasing the proportion of radon progeny attached to respirable and nonrespirable size dust particles). In wet drilling, water sprays from the drill onto

Table B-1 Mining radiation control methods

| Type of radiation | Control method | Description |
|---------------------------------|----------------|--|
| Radon, Thoron Gases and Progeny | Sealants | <p>Radon barrier coatings, made from water-based acrylic latex, water-based epoxies or other materials, painted on exposed rock surfaces. Coatings can reduce radon flow by 50 to 75 percent [92].</p> <p>Advantages: particularly useful in limited areas, i.e. intake airways with high radon emanations, lunchrooms, shops, etc. [92].</p> <p>Disadvantages: Too expensive to use throughout the mine.</p> |
| Radon, Thoron Gases and Progeny | Bulkheads | <p>Bulkheads seal off worked-out stopes or inactive mine areas. Bulkhead effectiveness increased when used with sealants and a slight negative pressure behind the bulkhead. Bulkheads can be made from brattice cloth, urethane foam, gunite, timber, etc. [93,92].</p> <p>Advantages: Cost-effective.</p> <p>Disadvantages: Bulkheads can leak if cracked, poorly sealed, or when barometric pressure decreases.</p> |

(Continued)

Table B-1 Mining radiation control methods (Continued)

| Type of radiation | Control method | Description |
|---------------------------------|----------------------------|---|
| Radon, Thoron Gases and Progeny | Backfilling | <p>A common uranium mining practice is to fill worked-out areas with mine waste rock and uranium mill tailings. One study showed an approximately 85 percent reduction in radon entering the stope after backfilling [93].</p> <p>Advantages: Reduces radon emanation, reduces ventilation requirements and provides ground support.</p> <p>Disadvantages: Uranium mill tailings can still release some radiation underground, perhaps including gamma radiation.</p> |
| Radon, Thoron Gases and Progeny | Air Cleaning | <p>Radon daughters are removed by an air cleaning apparatus, typically involving a filtering system.</p> <p>Advantages: Useful in limited areas where it is not feasible to install a large ventilation system [92].</p> <p>Disadvantages: High operating costs, lack of a commercial equipment source and equipment reliability problems [92].</p> |
| All Radiation | Medical Removal Protection | <p>If a person approaches or exceeds the lifetime limit on exposure, they are transferred to another job at a lower exposure level with retention of pay, if available, or are removed from work at full pay if another job is not available.</p> <p>Advantages: Protects individual miners against high cumulative exposures.</p> <p>Disadvantages: Spreads exposure over a larger number of people. This system works best when used with a reliable bioassay for exposure, which is not available in the case of radon gas or progeny. Medical removal may not be effective if intense, short-term exposure to inhaled alpha radiation is more hazardous than cumulative radiation exposure.</p> |

(Continued)

Table B-1 Mining radiation control methods (Continued)

| Type of radiation | Control method | Description |
|--|---|---|
| Uranium Ore Dust | Wet Drilling, hosing down muck piles, other uses of water to control dust | <p>The drills are equipped with automatic water valves that turn the water and compressed air on simultaneously. (These techniques have been used in mines since the 1930's.)</p> <p>Advantages: The water cuts down on radioactive uranium ore dust.</p> <p>Disadvantages: Difficult to set up in areas where water is scarce. The miners using the drill get wet.</p> |
| Uranium Ore Dust, Radon and Thoron Progeny | Blasting at the End of Shifts | <p>Dynamite blasting at the end of shift, instead of throughout the day, reduces exposure to dust and smoke. Also, radon gas levels tend to be high immediately after blasting [93].</p> <p>Advantages: Most miners have less exposure to dust and smoke particles and thus less radiation exposure.</p> <p>Disadvantages: Extra production schedule planning is necessary.</p> |
| Radon, Thoron Gases and Progeny | Minimizing Fan Shutdown | <p>This involves the use of fan maintenance, backup electrical systems, and spare fans to minimize fan shutdowns during working hours.</p> |
| Radon, Thoron Gases and Progeny | Ventilation - Blowing/ Positive Pressure | <p>Positive pressure at the rock surface is a barrier to radon flow. One drawback is that high positive pressure in one area may force the radon into nearby low pressure areas [92,93].</p> |

(Continued)

Table B-1 Mining radiation control methods (continued)

| Type of radiation | Control method | Description |
|----------------------------------|------------------------|--|
| Radon, Thoron Gases and Progeny | Ventilation -Exhaust | Exhaust ventilation removes radon, thoron and daughters, as well as diesel fumes, but it also increases the emission of radon from the surrounding rock by creating a negative pressure. |
| | Ventilation -Push-pull | Positive pressure ventilation is shut down during times when the mine is inactive, creating a temporary negative pressure. This results in energy savings during the shut down periods. The best ventilation method to use depends on the mine topography and production schedule. Ventilation methods may be most effective when used in combination with techniques that cut down on the area needing ventilation, such as bulkheads and backfilling [92,93]. |
| Radon Progeny and Thoron Progeny | Filter Respirators | The filter respirator covers the miner's mouth and nose and filters the mine air through fiber filters [94]. Advantages: As a temporary short-term protective measure, the half-mask respirator affords approximately greater than 90 percent efficiency in reduction of miner's exposure to radon daughters attached to dusts, fumes, and mists. Disadvantages: The respirators may hinder vision, be warm to use under some working conditions, add significant resistance to the miner's breathing and require careful maintenance to assure their continued effectiveness. Filter respirators must be carefully fitted to each wearer, using quantitative respirator fit tests. Only MSHA/NIOSH-certified respirators shall be used. |

(Continued)

Table B-1 Mining radiation control methods (continued)

| Type of radiation | Control method | Description |
|---|-------------------------------|---|
| Radon, Thoron Gases and Progeny | Supplied-air respirators | <p>The respirator is supplied with respirable breathing air from a central air supply.</p> <p>Advantages: As a temporary short-term protective measure, the supplied-air respirator affords a high degree of protection against all mine air contaminants.</p> <p>Disadvantages: The supplied-air respirator may hinder movement of the miner and the trailing air hose may get caught or tangled up in the mining environment. Respirators require careful maintenance to assure their continued effectiveness. Only MSHA/NIOSH-certified respirators shall be used.</p> |
| Uranium Ore Dusts, Radon, Thoron Gases and Progeny; maybe gamma | Robots or other mechanization | <p>The jobs with the highest dust levels could be mechanized further, thus minimizing the time during which the miner receives exposure. High dust exposure jobs include blasting, drilling, filling ore cars, putting in track, dumping waste, etc.</p> |

the rock while the drill operates, thus decreasing dust levels. Miners also wet down muck piles and the walls of some tunnels to control dust. Since the 1930's these two techniques have been used in some mines. Blasting increases uranium ore dust and radon gas levels remain high for about an hour afterwards [93]. Delaying blasting until the end of the work-shift removes the miner from an area with high dust and radon gas levels, and allows the ventilation system to reduce these levels before the miner returns to work.

3. Additional Control Methods

Air cleaning equipment, filter respirators, and separate air supplies are seldom used in the underground mining environment. An air cleaning apparatus can remove dust, but it is expensive compared to traditional ventilation methods and is most useful in circumscribed areas [92]. Filter respirators and supplied-air respirators are difficult to use in the mining environment and their use should be limited to emergency conditions, such as temporary excursions of the radon progeny concentrations above 1 WL. Respirators tend to restrict movement and vision, may be too warm to wear, have significant breathing resistance, and require careful maintenance and fitting to assure their continued effectiveness. Only MSHA/NIOSH-certified respirators shall be used. Another radon progeny control method is robotics or increased automation. Techniques, such as robotics, that minimize the time the miner spends in the high exposure areas of the mine and in activities such as drilling, blasting, or loading ore, will decrease the miner's radiation exposure. Although, at present, robotics has a limited place in the mines, it may be possible in the future to further automate the uranium ore mining process.

B. Administrative Controls

1. Medical Removal Protection

One type of administrative control is a medical removal protection (MRP) program. Under this program, when an individual's exposure approaches or exceeds a certain limit, the person is reassigned to an area with a lower exposure level. The MRP program has been very effective in reducing exposure in the (noncarcinogenic) lead industries [96]. In this case, blood lead levels could be used as a method to biologically monitor a worker's lead exposure. However, MRP has certain drawbacks when used as an administrative control for exposure to a known human carcinogen such as radon progeny in underground uranium mines.

First, according to our current knowledge of radiation carcinogenesis, it is prudent public health policy to presume that there is no threshold for radon-progeny-induced cancer, and thus no exposure can be assumed to be safe. Therefore, the high exposure individuals who are removed from the job are protected against further radon progeny risk, but the radon progeny exposure (and risk) is spread out over a larger population of workers. Second, at this time, there is no good biological monitoring method for radon progeny exposure because the primary health effect is a carcinogenic, rather than a toxicologic, response. Routine, periodic

sputum cytological examinations and chest X-rays are not effective screening tests for the detection of early reversible signs of lung cancer, and cancer itself may only appear after years of exposure. Finally, respirators (as they are presently designed) are very difficult to use in the underground mining environment.

2. Alarm Systems

Another type of administrative control involves the use of alarm systems. This method has been fairly effective in coal mines where continuous monitors for methane gas have been tied to alarm systems. Reliable continuous monitors for radon progeny are now technically feasible (see [89]) and could be connected to alarm systems, as well as the control center for the ventilation system. The person who controls the ventilation could increase air movement in mine areas with high radon progeny levels. Also, the continuous monitors might be useful for enforcement purposes, because the MSHA inspector would have a record of excessive radon progeny measurements levels since the last inspection. For recordkeeping and enforcement purposes, the use of data from continuous alarm-monitors would depend heavily on the reliability and validity of these devices, as well as their durability and security from tampering in the mine environment.

3. Contract Mining

Many underground uranium miners, especially those that drill, blast, and move ore, are given incentive bonuses for the volume of ore removed. Such a system encourages high productivity from the workers, but any time they spend on safety measures means less time to spend mining ore. The contract mining system also encourages miners to work overtime, thus increasing their cumulative internal and external radiation exposures. In addition, some miners, especially before the reduced demand for uranium, went from mine to mine working uranium ore one month and gold the next, getting radon progeny exposures in both locations.

This mobility of the work force makes it harder to monitor and track the miners' total radiation exposure, making it more likely that a miner could receive cumulative exposures in excess of current and future standards. One type of administrative control is to modify the contract mining system so that workers would have more incentive to protect their own health on the job. This issue needs further study and discussion, including input from the mining industries, unions, and contract miners.

GLOSSARY

Absorbed Dose: The amount of energy absorbed by ionizing radiation per unit mass. Absorbed doses are expressed in units of rads or grays, or in prefixed forms of these units such as millirad (mrad, 10^{-3} rad), microrad (urad, 10^{-6} rad), etc.*

The gray (Gy) is equal to 1 joule per kilogram (1 J/kg).

The rad is equal to 6.24×10^6 MeV per gram, or 100 ergs per gram.

One gray = 100 rad.

Additive Relative Risk Model: The relative risk from the combined exposure to radon progeny and smoking equals the sum of the risks from each exposure considered separately. One example of an additive linear relative risk model is:

$R = 1 + B_1 \text{WLM} + B_2 \text{PKS}$ where:

R = relative risk

B_1 = excess relative risk per unit of radon progeny exposure

B_2 = excess relative risk per unit of cigarette smoke exposure

WLM = working level months

PKS = cigarettes (in packs)

Association: Two variables are associated if one is more (or less) common in the presence of the second.**

Attributable (or Absolute) Risk: The rate of disease attributable to exposure⁺. For radon progeny exposure, it can be expressed as the arithmetic difference in risk between exposed and unexposed groups, in lung cancer deaths per year per WLM. One formula frequently used to calculate the attributable risk from radon progeny is:

$$AR = \frac{OBS - EXP}{PYR \times WLM} \times 10^6$$

Where: OBS = observed deaths in the cohort

EXP = expected deaths in the comparison group

PYR = person-years at risk

WLM = average working level months of radon progeny exposure

10^6 = 1 million

AR = attributable risk

Bias: An error in the measure of the association between two variables.**

Case-Control Study: Selection of study groups to be compared based on presence or absence of disease.**

Cohort Study: Selection of study groups to be compared based on presence or absence of exposure.**

Confounding Bias: A potential attribute of data. In measuring an association between an exposure and a disease, a confounding factor is one that is associated with the exposure and independently is a cause of the disease. Confounding bias can be controlled if information on the confounding factor is present.

Coulomb: The charge flowing past a point of a circuit in one second, when there is a current of one ampere in the circuit; also, the aggregate charge carried by 6×10^{18} electrons.

Electron Volt: The change in potential energy of a particle having a charge equal to the electronic charge (1.60×10^{-19} coulombs), moving through a potential difference of 1 volt.

Half-Life: The time required for a radioactive substance to decay to one half of its initial activity.

Follow-up Period: The length of time between a person entering an epidemiological study cohort and the present report (or the end of the study).

Incidence Rate: The number of new cases of disease per unit of population per unit of time, e.g., 3/1000/year.**

Interaction: The association of one factor (occupation) with disease modified by the effect of another factor (smoking). The measure of association can be the rate or odds ratio. This follows a nonmultiplicative model (may be additive).

Ionizing Radiation: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Lagging Exposures: Lagging of the cumulative exposure assigned to a miner. Some authors consider that radon progeny exposures are "redundant" if they occur after lung cancer is induced. Some authors believe that cumulative exposures should be lagged by a certain number of years (5 or 10), to exclude redundant exposures occurring during these years. For example, Radford and St. Clair Renard [5] discounted the last 5 years of exposures from the cumulative total WLM assigned to each case of lung cancer in their analysis.

Biologic Latent Period: The time between an increment of exposure and the increase in risk attributable to it.+

Epidemiologic Latent Period: The time between first exposure and death in those developing the disease during the study interval.

Linear Hypothesis: The hypothesis that excess risk is proportional to dose.

Matching: A procedure to reduce the biasing effect of a confounding variable. A feature of selection to study groups.**

Multiplicative Relative Risk Model: The relative risk from the combined exposure to radon progeny and smoking equals the product of the risks from each exposure considered separately. One example of a multiplicative linear relative risk model is:

$R = 1 + B_1 \text{WLM} + B_2 \text{PKS}$ where:

R = relative risk

B_1 = excess relative risk per unit of radon progeny exposure

B_2 = excess relative risk per unit of cigarette smoke exposure

WLM = working level months

PKS = cigarettes (in packs)

Person-Years (PY): A standard technique for handling variable follow-up periods; multiply the number of persons by the number of years of follow-up.

Person-Years at Risk (PYR): In a lifetable analysis, the number of PY at risk of dying from disease, usually calculated from the time the miner enters the cohort until death or the end of follow-up. Some authors adjust the PYR for an assumed 10-year latent period for lung cancer by subtracting PYR accumulated during the first 10 years after a miner starts to work underground (see above, (Lagging)).

Potential Alpha Energy Concentration (PAEC): May cause biological damage during the radioactive decay of radon or thoron gases and their progeny, is measured in units called Working Levels (see below).

Proportional Mortality Ratio (PMR): The ratio of two mortality proportions, expressed as a percentage, often adjusted for age or time differences between the two groups being compared.**

Prospective: A study characteristic. Disease has not occurred in study groups at the start of a study.**

Units of Radioactivity: Curie and Becquerel

1 curie = 2.22×10^{12} disintegrations/minute

1 becquerel (Bq) = 1 d/sec

1 picocurie (pCi) = 2.22 d/minute

Radioactive Decay: Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles, photons, or both.

Radon (Rn) or Radon and its Progeny: Specifically refers to the "parent" noble gas (Rn-222), and its short-lived alpha-radiation-emitting radioactive decay products ("progeny" or "daughters"). Radon is a gas, the radon progeny are radioactive solids.

Rate: The number of cases per unit of population.

Rate Ratio: One rate divided by another rate with the same dimensions. A measure of association without a unit.**

Relative Risk: The ratio of rates in exposed and nonexposed populations. One formula frequently used to calculate the relative risk for radon progeny exposure is:

$$\text{ERR} = \frac{\text{OBS/EXP} - 1}{\text{WLM}} \times (100 \text{ WLM})$$

Where: ERR = excess relative risk
OBS = observed deaths in the cohort
EXP = expected deaths in the comparison group

Rem and Sievert

rem = rad x QF x modifying factors
sievert = grays x QF x modifying factors
10 mSv = 1 rem

Rads and rems are comparable (i.e., the quality factor (QF) = 1) when dealing with beta particles and gamma photons. The QF for alpha particles from inhaled radon progeny are generally considered to be in the range of 10 to 20.

Retrospective: A study characteristic. Disease has already occurred in study groups at the start of a study.**

Standardization: A procedure to reduce the biasing effect of a confounding variable. A feature of data analysis.**

Standardized Mortality Ratio (SMR): The ratio of mortality rates, expressed as percentage, usually adjusted for age or time differences between the two groups being compared.**

Synergism: The combined action of two factors which is greater than the sum of the actions of each of them.

Thoron: A radioactive gas (Rn-220), sometimes found in the presence of radon (Rn-222). Thoron progeny are the solid, short-lived, alpha radiation emitting decay products (progeny or daughters) of thoron gas.

Working Level (WL): A standard measure of the alpha radiation energy in air. This energy can come from the radioactive decay of radon (Rn-222) and thoron (Rn-220) gases. The working level is defined as any combination of short-lived radon decay products per liter of air that will result in the emission of 1.3×10^5 million electron volts (MeV) of alpha energy.

Working Level Month (WLM): A person exposed to 1 WL for 170 hours is said to have acquired an exposure of one Working Level Month. The Mine Safety and Health Administration defines a Working Level Month as a person's exposure to 1 WL for 173 hours.

- * Taken from Shapiro (1981) [1].
- ** Taken from Monson (1980) [98].
- + Taken from Thomas et al., (1985) [99].

APPENDIX II

**QUANTITATIVE RISK ASSESSMENT OF LUNG
CANCER IN U.S. URANIUM MINERS**

by

Richard W. Hornung, Dr. P.H.
Theodore J. Meinhardt, Ph.D.
National Institute for Occupational Safety and Health
Centers for Disease Control
Cincinnati, Ohio 45226

January 16, 1986

ACKNOWLEDGMENT

The authors would like to acknowledge the advice and input of Dr. Dale Hattis of the Massachusetts Institute of Technology's Center for Policy Technology and Industrial Development, which was especially useful in considering exposure assessment and the characteristics of carcinogenesis. Appreciation is also acknowledged for the assistance of Robert Roscoe of NIOSH in providing updated mortality status for the study group.

I. INTRODUCTION

A report evaluating epidemiologic studies of lung cancer in underground miners was recently sent to the Mine Safety and Health Administration (MSHA) by the National Institute for Occupational Safety and Health (NIOSH). That report concluded that prolonged exposure to radon progeny at the current standard of 4 WLM/year produced an elevated risk of death from lung cancer. It is the objective of this report to make quantitative risk estimates for various levels of cumulative exposure. In addition, other factors influencing the exposure-risk relationship will be identified and quantified whenever possible.

This report is based upon data collected from a cohort consisting of 3366 white underground uranium miners working in the Colorado Plateau (located within the states of Colorado, Utah, New Mexico and Arizona). The actual risk estimates were computed from data on 3346 members of the cohort. Ten original members were determined to have had no record of underground mining, four were non-white, and six had inadequate cigarette smoking information.

Entry into the cohort was defined by race, sex, working at least one month in underground uranium mines, volunteering for at least one medical survey between 1950 and 1960, and providing social and occupational data of sufficient detail [Lundin et al. 1971].

NIOSH has now updated the mortality experience of the cohort through December 31, 1982. Lung Cancer mortality was defined as anyone assigned an International Classification of Disease (ICD) code of 162 or 163 (same designation in Sixth through Ninth Revisions). Previous analyses of this cohort reported by Waxweiler et al. [1981] and Whittemore and McMillan [1983] considered follow-up only through 1977. Table 1 presents a comparison of vital status of the cohort at the end of 1977 and 1982.

Table 1. Status of Data Base

| | 1977 | | 1982 | |
|--------------|--------|---------|--------|---------|
| | Number | Percent | Number | Percent |
| Alive | 2,388 | 71.4 | 2,132 | 63.7 |
| Deceased | 958 | 28.6 | 1,214 | 36.3 |
| Lung Cancer | 187 | 19.5 | 255 | 21.0 |
| Other Causes | 771 | 80.5 | 959 | 79.0 |
| Total | 3,346 | 100.0 | 3,346 | 100.0 |

II. PROTOCOL FOR STATISTICAL ANALYSIS

A. Type of Analysis Used

Much of the epidemiologic work in the past regarding the analysis of mortality in occupational cohorts has involved modified life table analysis. This form of analysis has a strong appeal due to its familiarity and ease of interpretation. It is mathematically straight forward since person-years at risk are simply divided into a number of strata and age-calendar year specific mortality rates from some reference population are applied to each. The U.S. population is often used as the reference population in such life table analyses. This expected mortality is then compared to the observed mortality via a ratio defined as:

$$SMR_j = \frac{\sum_i O_{ij}}{\sum_i E_{ij}}$$

where SMR = standardized mortality ratio for cause j
 O_{ij} = the observed number of deaths for cause j
in stratum i
and E_{ij} = the expected number of deaths for cause j
in stratum i from reference population rates

If the total number of observed deaths in all of the strata of interest is large and if the reference population is the appropriate comparison group, this would be the method of choice. No modeling would be needed in such a situation. However, after stratification by age, race, sex, calendar year, other confounders, and finally the exposure of interest, there are seldom enough observed deaths to make rates in these strata reliable.

Another problem frequently encountered is a fundamental difference in certain etiologic characteristics between the study population and the reference population. For example, the study group may smoke at substantially different rates than the reference population. Often the occupational study group is "healthier" than the reference population due to selection criteria for employment (Enterline [1976]). This is usually referred to as the "healthy worker effect." An alternative to use of the modified life table approach is some form of statistical modeling. Modeling to estimate health risks is necessary when conclusions must be drawn about risk in regions of the exposure-response relationship for which data are too sparse to estimate risk directly. The use of models also permits risk estimates to be simultaneously adjusted for confounders, such as age or co-carcinogenic exposures, as well as interactions between exposure and other risk factors. This flexibility is particularly important in making risk estimates at relatively low cumulative exposures when using the Colorado Plateau data. Most miners in this cohort were exposed to high levels of radon progeny (mean exposure = 834 WLM). Since primary interest in risk estimates is below 120 WLM based on current exposures, some type of statistical model is essential.

There have been a number of types of models suggested for examination of cause-specific mortality as a function of various risk factors. The two most popular types of models are the absolute risk model and the relative risk model. The absolute risk model can be written as:

$$R(t; \underline{z}) = R_0(t) + R(\underline{z}, \beta)$$

where $R(t; \underline{z})$ is the incidence at age t for someone with risk factors \underline{z} , $R_0(t)$ is the baseline or background incidence at age t and $R(\underline{z}, \beta)$ is the incremental incidence as a function of the risk factors \underline{z} , and coefficients which are estimated from the data. This form of risk model was not used in the risk assessment since it had been rejected due to poor fit to the U.S. uranium miner data by Lundin et al. [1979].

In contrast, the relative risk model generally takes the form:

$$R(t; \underline{z}) = R_0(t) R(\underline{z}, \beta).$$

This model assumes that excess risk is proportional to background incidence rates. Relative risk models have become increasingly popular in recent years and were found to provide good fits to the data from earlier follow-ups of the U.S. uranium miners cohort by Lundin et al. [1979] and Whittemore and McMillan [1983]. This type of model has been selected as the basic analytical method for this report.

B. The Proportional Hazards Model

A relative risk model which is particularly well-suited to longitudinal mortality studies is one proposed by Cox [1972]. This model is commonly referred to as the Cox proportional hazards model. A major advantage of this approach over the more common life table method is that it permits the use of internal comparison groups while controlling simultaneously for such confounders as cigarette smoking, age, and year of birth. In addition, time-dependent covariates such as cumulative exposure may be incorporated into the model. This is essential in any longitudinal study where follow-up and the exposure period overlap. Relative risk estimates are based on rate ratios similar to those produced in the modified life table analysis. That is, the Cox model operates in a dynamic framework by considering incidence rates over the entire period of follow-up.

The Cox model can be expressed mathematically as:

$$\lambda(t; \underline{z}) = \lambda_0(t) \exp(\underline{\beta} \underline{z}(t))$$

where $\lambda(t; \underline{z})$ for this study is the age-specific lung cancer mortality rate for a miner with exposure and other risk factors represented by a covariate vector \underline{z} . The underlying age-specific lung cancer mortality rate for the unexposed is represented by $\lambda_0(t)$. The function $\exp(\underline{\beta} \underline{z})$ is generally used to model risk of death from the cause of interest which depends upon the risk factors \underline{z} and the coefficients $\underline{\beta}$ which are estimated from the data.

C. Alternative Forms of the Risk Function

Although the exponential or log-linear function $\exp(\beta z)$ is the usual choice of a model for risk, any positive function may be used as long as the risk function is equal to 1.0 when the coefficients are all equal to zero. The most common alternative risk functions are the linear $(1 + \beta z)$ and the power function $(\exp(\beta \ln z) = z^\beta)$. All three forms of risk functions were considered in modeling the U.S. uranium miners data.

D. Results of Model Development

1. Identification of Confounders and/or Effect Modifiers

Cumulative exposure as measured by total WLM for each miner was the primary exposure variable. Since cigarette smoking is known to have a strong effect upon the risk of lung cancer, cumulative smoking history as measured in pack-years was also included in the model. Another risk factor strongly associated with lung cancer mortality is age. This was tightly controlled by using age as the time dimension t in the model $\lambda(t; z)$. That is, the age at death of each lung cancer victim was recorded and all other miners alive and at risk were compared to him at that age. In this way, the cumulative exposure to radon daughters and pack-years of cigarettes were incorporated as time-dependent covariates by calculating their values at each age of death from lung cancer. This assures that proper age-adjusted comparisons were made throughout the period of follow-up.

A number of other variables were examined in developing the appropriate risk model. A list of all potential risk factors considered for inclusion in the model are provided in Table 2. These variables were considered independently as potential confounders in a stepwise fashion (both backward and forward selection procedures) and also as potential effect modifiers by assessing their interaction with cumulative radon daughter exposure.

An attempt was made to compare the fit of each of the three models during the model development stage of the analysis. However, it soon became apparent that the linear model did not fit well over the full range of radon daughter exposures and cumulative smoking levels. In fact, the iterative solution to the likelihood equations would not converge when using the linear model when both cumulative exposure and pack-years of smoking were both entered simultaneously (either as linear or linear-quadratic forms). The linear model could only be made to converge when the model was restricted to cumulative exposure below 600 WLM with no other covariates included. The restricted linear model resulted in a non-significant result in this exposure range and was subsequently eliminated from consideration.

Of the remaining two types of relative risk models (log-linear and power function), the covariates found to be most highly associated with lung cancer incidence rates were cumulative exposure (WLM), cumulative smoking (packs), and age at initial exposure (months). Table 3 illustrates the form and degree of fit as measured by the likelihood

Table 2. Regression Variables Considered in Development of Model

| Variable | Units | Median | Range |
|--------------------------------------|---|--------|-------------|
| Cumulative Exposure | Working Level Months (WLM) | | 0.3-10,000+ |
| Average Exposure Rate | WLM/month | 10.3 | 0.03-998 |
| Cumulative Cigarette Smoking* | Packs | 10,027 | 0.0-61,000 |
| Smoking Rate | Packs/day | 0.64 | 0.0-3.5 |
| Age at Initial Exposure | Months | 348.4 | 101-877 |
| Calendar Year of Initial Exposure | Year | 1954 | 1908-1963 |
| Birth Year | Calendar year | 1921 | 1877-1948 |
| Height | Short (<68 inches) Medium (68-70 inches) Tall (\geq 70 inches) | | |
| Duration of employment | Months underground | 48.0 | 1-371 |
| Years of Prior Hardrock Mining** | Years | 0.0 | 0-42 |

*20.4 percent never smoked.

**62 percent had no prior hardrock mining.

Table 3. Comparison of Log-Linear and Power Functions Models

| Risk Factor | Coefficient | χ^2 | P-value |
|-------------------------------------|-------------|----------|---------|
| <u>Log-linear Model</u> | | | |
| Cumulative exposure (WLM) | 0.897 | 125.4 | <0.001 |
| Cumulative cigarettes (packs) | 0.063 | 44.6 | <0.001 |
| (WLM) ² | -0.089 | 44.5 | <0.001 |
| (Packs) ² | -0.002 | 10.5 | 0.001 |
| Age at Initial Exposure (months) | 0.0022 | 7.9 | 0.005 |
| LIKELIHOOD RATIO $\chi^2 = 205.8$ | | | |
| <u>Power Function Model</u> | | | |
| Ln(Cumulative Exposure+BGR) | 0.713 | 135.3 | <0.001 |
| Ln(Cumulative Smoking+BGS) | 0.295 | 35.3 | <0.001 |
| Age at Initial Exposure | 0.0023 | 8.7 | 0.003 |
| LIKELIHOOD RATIO $\chi^2 = 219.9$ | | | |

¹BGR - background radon exposure = 0.2 WLM/year
 BGS = background cigarette smoking = 0.005 packs/day

ratio for these two models. The log-linear model required the addition of quadratic terms in cumulative exposure and cigarette smoking to provide an adequate fit. This was not necessary when developing the power function model. As shown in Table 3, the power function model provided the best fit to the data and will be used hereafter in the risk assessment.

Since the power function model involves the natural logarithms of cumulative exposure and cumulative cigarette smoking, zero values of these variables were not permitted. In order to avoid this an estimate of cumulative background exposure was added to each miner's cumulative radon daughter and cigarette totals. Based upon estimates of the NCRP (Report No. 77, 1984), 0.2 WLM per year since birth were added to each miner's exposure totals. This is the estimated background exposure in the U.S. and is also the amount used by Whittemore and McMillan [1983] in an earlier analysis. In a similar fashion 0.005 packs per day were added for each day since birth to the cumulative smoking totals based upon estimates of Hinds and First [1975].

Of particular interest is the joint effect of exposure to radon daughters and cigarette smoking. Therefore, the interaction of radon daughter exposure and cigarette smoking was included in the multiplicative power function model. The results showed a negative, borderline significant result ($\beta=0.087, p=0.058$). When a similar analysis was run with mortality data complete only through 1977, there was no indication of a significant negative effect. Therefore, based on more complete follow-up through 1982, the joint effect of radon daughter exposure and cigarette smoking appears to be slightly less than multiplicative but greater than additive. This is similar to the finding of Thomas and McNeill [1985] in their grouped data analysis of the five major radon daughter cohorts. It is still consistent with a synergistic effect of radon exposure and cigarette smoking which is usually defined as a joint effect exceeding the sum of the individual effects.

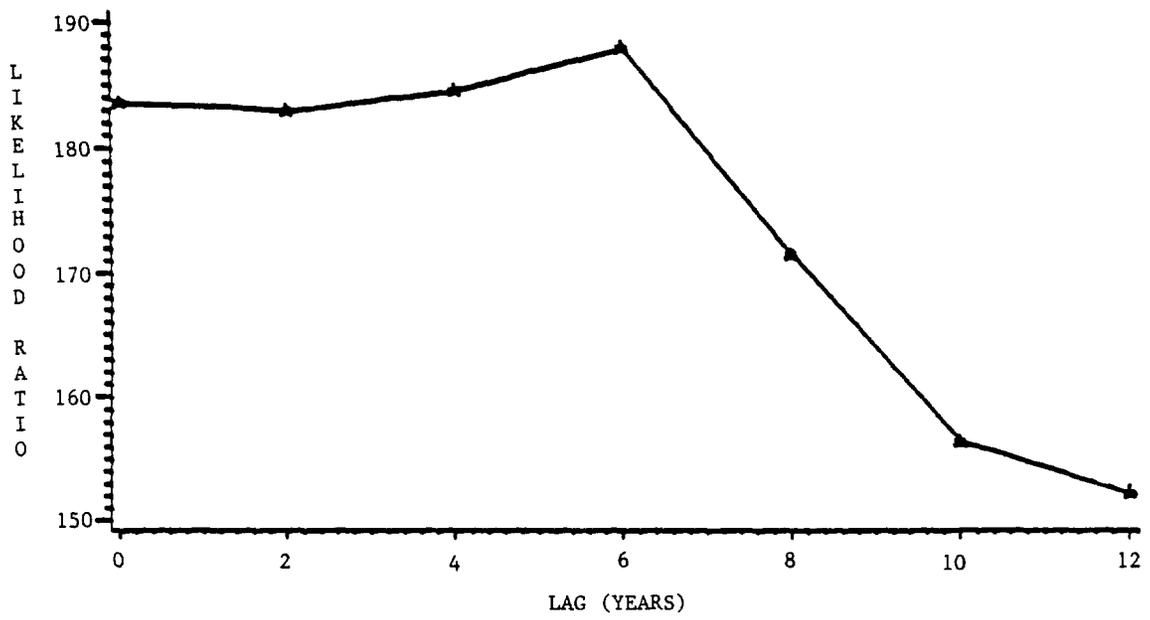
2. Weighting Exposure Over Time

An important consideration in fitting any of these models was the proper time-weighting of exposure. Since most forms of cancer, including lung cancer, have relatively long latency periods between exposure and manifestation of the disease, some weighting of exposure over time is appropriate. The most common weighting scheme is commonly referred to as lagging. This involves elimination of any exposure accumulated in a specified period of years before death from lung cancer. This provides a way of considering only that exposure that had a reasonable chance of causing death from lung cancer. Obviously exposures received in the few years immediately prior to lung cancer deaths are ineffective in the exposure-response relationship.

In order to investigate the appropriate number of years to lag exposure in this cohort, a series of lags ranging from 0 to 12 years was used. Figure 1 illustrates the results of these trials. It is evident from the improved fit, as measured by the log-likelihood of the model, that a

FIGURE 1

EFFECT OF LAGGING ON LIKELIHOOD OF MODEL



lag of 6 years for cumulative exposure is the best choice for this analysis. Cumulative cigarette smoking was rather insensitive to the amount of lag in the range of 0 to 12 years. Therefore, for the purpose of consistency cumulative smoking was also lagged 6 years. This contrasts to the lag of 10 years chosen by Whittemore and McMillan [1983] for these data and also by Muller et al. for the Canadian data. Their choices were somewhat arbitrary and largely based on knowledge that most cancers involve relatively long latency periods. The implications of a shorter lag will be discussed in a later section of this report.

An issue related to lagging of cumulative exposure and cumulative cigarette smoking is the lack of information on these variables in recent years. Radon daughter exposure was last updated in 1969. However, the absence of current exposure information should have minimal impact upon this analysis since over 90% of the miners in the cohort had retired from uranium mining for more than one year by 1969. Those few who continued mining were exposed at levels considerably less than those experienced in earlier years. Since cigarette smoking status was also unknown after 1969, all miners still smoking at that time were assumed to continue at their last recorded smoking rate. NIOSH is currently conducting a survey of radon daughter exposure and cigarette smoking status subsequent to 1969, but this information will not be available for at least another year.

The aim of lagging exposure is the elimination of exposure which is not etiologically responsible for lung cancer mortality. An implicit assumption in the use of this technique is that exposure changes from completely effective to completely ineffective at one instant in time. The actual form of this weighting function is illustrated in Figure 2. Because of the biological implausibility of such a situation, Land [1976] proposed that the effectiveness of cumulative exposure be linearly phased in over a period of several years. An illustration of such a weighting function is provided in Figure 3. Consequently, we tried various combinations of lagging and linear partial weighting with the combination illustrated in Figure 3 providing the best fit, i.e. a lag of 4 years followed by linear partial weighting in the period 4-10 years prior to death from lung cancer. This scheme provided a fit essentially the same as that of a simple lag of six years but was chosen over lagging because of its biological plausibility.

FIGURE 2

EXAMPLE OF SIX YEAR LAG WEIGHTING SCHEME

150

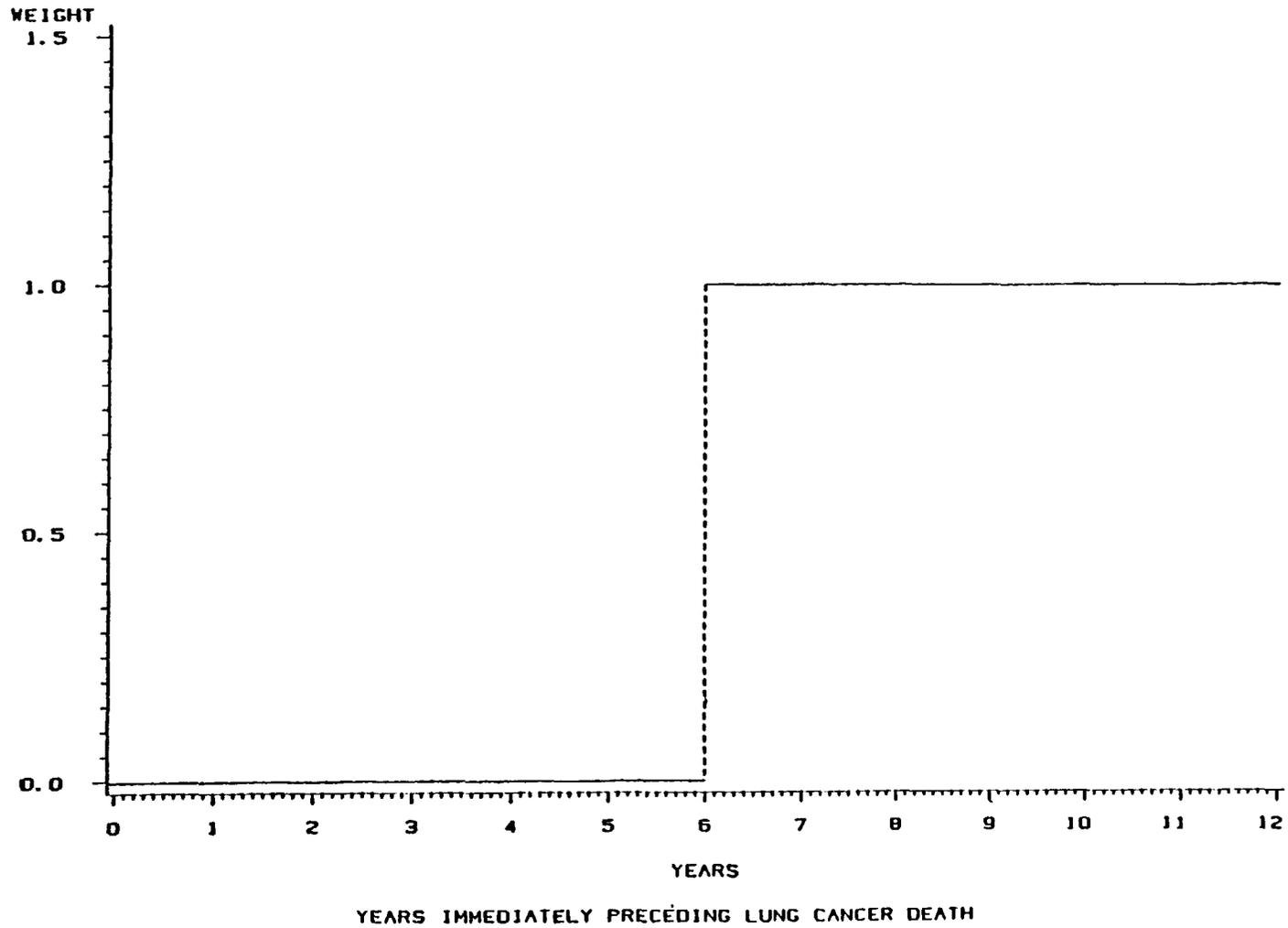
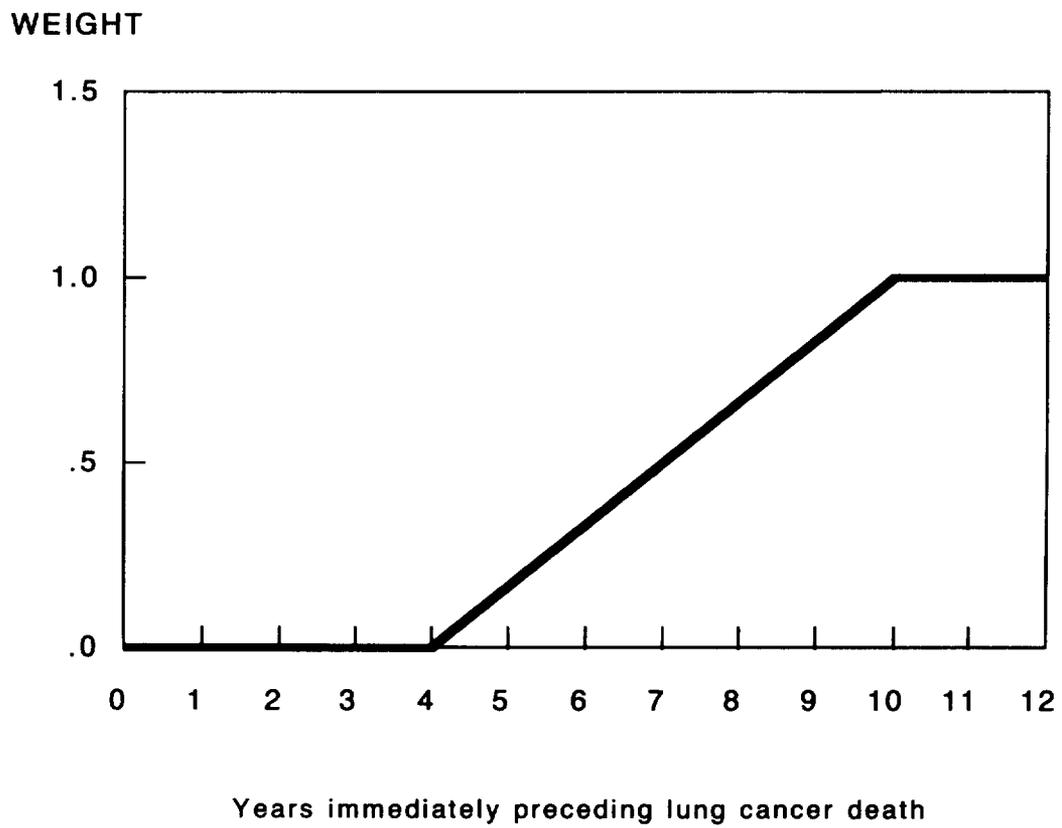


FIGURE 3
EXAMPLE OF LAGGING WITH PARTIAL WEIGHTING



III. INFLUENCE OF TEMPORAL FACTORS

A. Exposure-Rate Effect

Perhaps the most difficult aspect of producing a valid quantitative risk assessment is dealing with the effects of various time-related factors upon the exposure-risk relationship. One very important temporal influence concerns the two components of cumulative exposure itself. In most longitudinal studies the quantitative exposure index is some form of cumulative exposure. However, cumulative exposure is actually the product of duration of exposure and intensity or rate of exposure. When one uses cumulative exposure in assessing risk, the implicit assumption is that high exposure rates for short periods of time are equivalent etiologically to low exposures for long periods of time, all else being equal.

A number of investigators have examined the effect of exposure rate in the U.S. uranium miner data. Whittemore and McMillan [198]) found no statistically significant effect of exposure rate. Lundin et al. in the 1971 monograph concluded that there was no significant evidence of an exposure rate effect in the 120-360 WLM cumulative exposure range. These investigators apparently defined exposure rate as the ratio of total cumulative exposure and duration of employment (defined as the period of time between first and last employment in underground uranium mining work histories). For most forms of employment, this is the accepted definition of average exposure rate. However, underground uranium mining is a very sporadic form of employment. The actual time spent underground was often a relatively small fraction of the total employment history. Therefore, exposure rate as defined by cumulative exposure divided by the number of months actually spent underground is often a very different measure than that obtained by using duration of employment in the denominator.

Consequently, the effect of exposure rate was re-examined using the actual average exposure rate experienced while underground, eliminating any gaps in employment. Although earlier analyses using total duration of employment produced negative but non-significant results, the refined definition showed a statistically significant negative exposure rate effect ($\beta = -0.043$, $p < 0.001$) as shown in Table 4. This implies that among groups of miners receiving equivalent cumulative exposures, those exposed to lower levels for longer periods of time are at greater risk of lung cancer. Because the coefficient is relatively small, however, an appreciable effect upon risk of lung cancer would not be expected unless rates were different by an order of magnitude, i.e., a miner with exposure received at a rate ten times lower than a miner of the same age, smoking habits, and cumulative exposure would have $(0.1)^{-0.043} = 1.104$ or 10.4% greater risk of lung cancer.

Because a negative exposure rate effect is very important and potentially controversial, it was examined in more depth. Of particular interest was the possibility that this effect was different at low versus high cumulative exposure levels. Consequently, the homogeneity of this effect across the full exposure range was examined by forming two sub-cohorts: one below the mean exposure (834 WLM) and one above the mean. The interaction of the exposure rate effect with these two strata was then tested. Results showed a significant interaction ($\beta = 0.157$, $P = 0.019$). The direction of the

Table 4. Quantitative Relative Risk Model

| Risk factor | Coefficient | χ^2 | P-value |
|--|-------------|----------|---------|
| Ln(cumulative exposure+BGR)(WLM) ¹ | 0.731 | 139.5 | <0.001 |
| Ln(cumulative cigarette smoking+BGS) (packs) ² | 0.291 | 34.5 | <0.001 |
| Age at initial exposure (months) | 0.0023 | 8.8 | 0.003 |
| Ln(exposure rate)(WLM/month) | -0.043 | 18.6 | <0.001 |
| <u>Exposure Rate Interaction Model</u> | | | |
| Ln(cumulative exposure+BGR) | 0.660 | 101.4 | <0.001 |
| Ln(cumulative cigarette smoking+BGS) | 0.292 | 34.8 | <0.001 |
| Age at initial exposure | 0.0024 | 9.2 | 0.002 |
| Ln(exposure rate) | -0.198 | 8.9 | 0.003 |
| Ln(exposure rate) x exposure category: | 0.157 | 5.5 | 0.019 |
| Exposure <834 WLM = 0 Exposure ≥834 WLM = 1 | | | |

¹Background for cumulative radon daughter exposure: BGR=0.4 WLM/year
²Background for cumulative cigarette smoking: BGS=0.005 packs/day

interaction indicated that the exposure rate effect was stronger in the lower cumulative exposure range (0-834 WLM). Specifically, a miner who received total exposure below 834 WLM at rate one tenth as great as another miner of the same age, smoking status and cumulative exposure would have a 58 percent greater risk of lung cancer. However, the increased risk would only be 10 percent at the lower exposure rate for miners in the 834-10,000 WLM range.

Although a statistically significant negative exposure-rate effect had not been found previously in this U.S. cohort, there is considerable evidence of such findings in animal studies of high LET radiation. Raabe et al. [1983] reported a strong low dose-rate effect in beagles exposed to internally deposited isotopes of radium and strontium. Risk of bone cancer was as much as ten times as great per unit dose for low rates as compared to the highest rates used. Cross et al. [1980] found a negative dose-rate effect for risk of lung tumors in rats exposed to airborne radon daughters. Chameaud et al. [1981] found similar results in a French study of Sprague-Dawley rats exposed to inhalation of radon decay products. Hill et al. [1982] found reduced dose rates of fission-spectrum neutrons produced significantly higher neoplastic transformation rates per rad in cell cultures of C3H mouse embryos. Although all of these studies show low dose-rate effects, no study as yet, animal or human, has investigated such effects at the very low dose rates currently found in well-ventilated uranium mines.

B. Calendar Time

It is well-known that mortality patterns change over time. Such exogenous risk factors as the prevalence of smoking and alcohol consumption, medical care, and various life style characteristics are all influenced by a changing society. Therefore, the effect of calendar time upon risk estimates, often called the cohort effect, must be controlled. The analysis of the U.S. uranium miners cohort was stratified by decade of birth so that miners dying of lung cancer were compared only to those members of the cohort at the same age and who were born within 10 years of the case. The usual assumption in a stratified analysis is that baseline mortality rates may be different from stratum to stratum but the relative risk is the same across all strata for miners with comparable risk factors. In order to check this assumption, the interaction of cumulative radon daughter exposure and birth decade was examined. Results indicated a statistically significant positive interaction ($\beta=0.173, P=0.002$). This implies that miners born in later decades are at a greater risk of lung cancer per unit of exposure when compared to miners of the same age born earlier. Since miners born in later decades were exposed at lower exposure rates, this result could be associated with the negative exposure rate effect described earlier.

C. Multistage Theory of Carcinogenesis

One of the most popular theories for explaining the temporal patterns in mortality studies of carcinogenesis is the multistage model. Originally proposed by Muller [1951] and Nordling [1953] and later refined by Armitage and Doll [1961], the multistage theory predicts an increase in cancer incidence as a function of time since exposure to some carcinogen. In

general, the theory proposes that a malignant tumor arises from a single cell which has undergone a series of heritable changes. The changes may be thought of as distinct stages in the carcinogenic process, each with a low probability of occurrence and a slow progression time in the absence of carcinogenic exposures. A carcinogen may act on any or all of the stages in this process. Carcinogens affecting the first stage are commonly referred to as initiators, while those affecting later stages are called promoters or progressors. Initiators are characterized by long latency periods between initial exposure and death, often exceeding 20 years. Promoters, on the other hand, usually have shorter latent periods since fewer stages must be transgressed before a malignant cell is produced. It is impossible to prove whether or not the mathematical form of the multistage model actually holds in a given situation. However, a number of its predictions have been verified experimentally by Peto et al. [1975]. Therefore, if one subscribes to some form of the multistage model, it is possible to predict whether exposure acts at an early or late stage in the carcinogenic process by examining the temporal patterns in the data. Whittemore [1977], Day and Brown [1980], and Brown and Chu [1983] have all reported the effect on excess relative risk of age at initial exposure and time since cessation of exposure. By examining these factors, we may better understand the underlying cancer mechanism operative in this cohort.

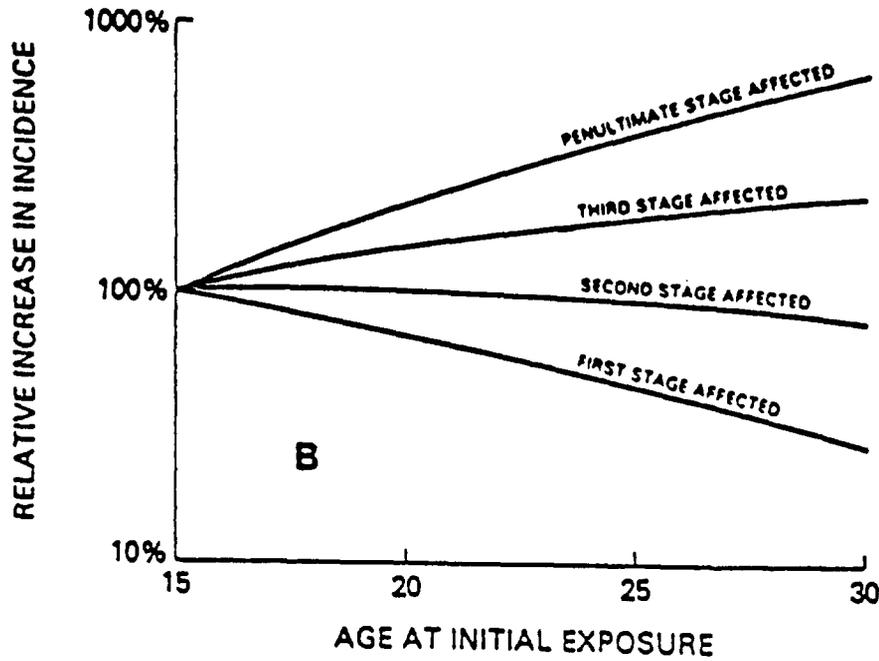
D. Age at Initial Exposure

Whittemore [1977] considered the multistage model using three exposure scenarios: single exposure at one point in time, continuous exposure at a constant rate, and exposure of varying intensity. When considering the latter category (the usual occupational situation) she found that excess relative risk was a decreasing function of age at initial exposure if an early stage was affected. When a late stage is affected by exposure, however, excess relative risk is an increasing function of age at initial exposure.

Day and Brown [1980] predicted the functional relationship between excess relative risk and age at initial exposure for the first four stages of a five-stage process when duration was held constant. Figure 4 illustrates their findings which are in qualitative agreement with those of Whittemore. Results of the analysis in our data, as illustrated in Table 4, indicate a positive and statistically significant coefficient for age at initial exposure ($\beta=0.0023$, $P=0.003$). This implies that miners initially exposed at later ages are at greater risk of lung cancer than those exposed at younger ages, all else being equal. Specifically, a miner with the same radon daughter exposure and smoking history who was initially exposed ten years (120 months) later in age than another miner, would have $\exp(0.0023 \times 120) = 1.32$ or 32% higher risk of lung cancer. This result is consistent with the effect of radon daughters occurring at a late stage in the carcinogenic process. A similar age effect was reported by Mancuso et al. [1977] in an analysis of cancer risk in the Hanford workers exposed to whole-body radiation.

FIGURE 4

EFFECT OF AGE AT INITIAL EXPOSURE ON A MULTISTAGE MODEL



An analysis of age at start of smoking among miners resulted in a negative but non-significant coefficient ($\beta=0.0016, p=0.22$). This would imply that cigarette smoking in this cohort acted at an early to intermediate stage. It could also be consistent with the hypothesis of Doll and Peto [1978] that smoking acts at both early and late stages, which would tend to obscure predictive ability of age at start of smoking. A plot of the effect of age at initial exposure for both radon daughters and cigarette smoking is given in Figure 5.

E. Time Since Cessation of Exposure

Day and Brown [1980] predicted the effect upon relative risk of time since cessation of exposure when a multistage model is assumed. They found that when exposure begins some time after infancy, excess relative risk increases, peaks, and then decreases with time since termination of exposure when the first stage is affected. When the penultimate (next to last) stage is affected, relative risk strictly decreases with time after last exposure. Figure 6 illustrates their predictions for the effect of time since cessation of exposure on the first four stages in a five stage model with duration of exposure fixed at five years.

In order to investigate the effect of cessation of exposure on this cohort, all miners were identified who had indicated retirement from uranium mining during the course of follow-up. Approximately 95% of the cohort had retired for more than one year prior to 1970. The average time since last exposure was 18.0 years for those miners not dying of lung cancer and 9.9 years for lung cancer cases.

The time in months since last exposure was entered as a time-dependent covariable in the original model containing log of exposure, log of smoking, and age at initial exposure. The estimated coefficient of this term was negative and highly significant ($\beta=-0.0056, p<0.001$). Thus a miner's chances of surviving lung cancer increase dramatically with each year outside the mines. Specifically, the model predicts that the risk of lung cancer 10 years after mining uranium is $\exp(-0.0056 \times 120) = 0.511$ relative to someone still mining with the same cumulative exposure, smoking history, and age.

When a similar analysis of time since cessation of cigarette smoking was run, the results were inconclusive. The coefficient was very small and non-significant ($\beta=0.003, p=0.75$). However, since a relatively small number of miners were ex-smokers (7.7%) there is little power for detection of such an effect even if it actually exists. Figure 7 illustrates the effect of time since last exposure for both radon daughters and cigarette smoking.

The implication of these results are essentially the same as that obtained by examination of age at initial exposure. The strong negative effect of time since last exposure implies that radon daughters act at a late stage in the carcinogenic process. The effect of stopping cigarette smoking, while based on a small amount of data, still indicates either an intermediate stage effect or a combination of early and late stage effects.

FIGURE 5

EFFECT OF AGE AT INITIAL EXPOSURE ON RISK
RELATIVE TO MINER BEGINNING AT AGE 15

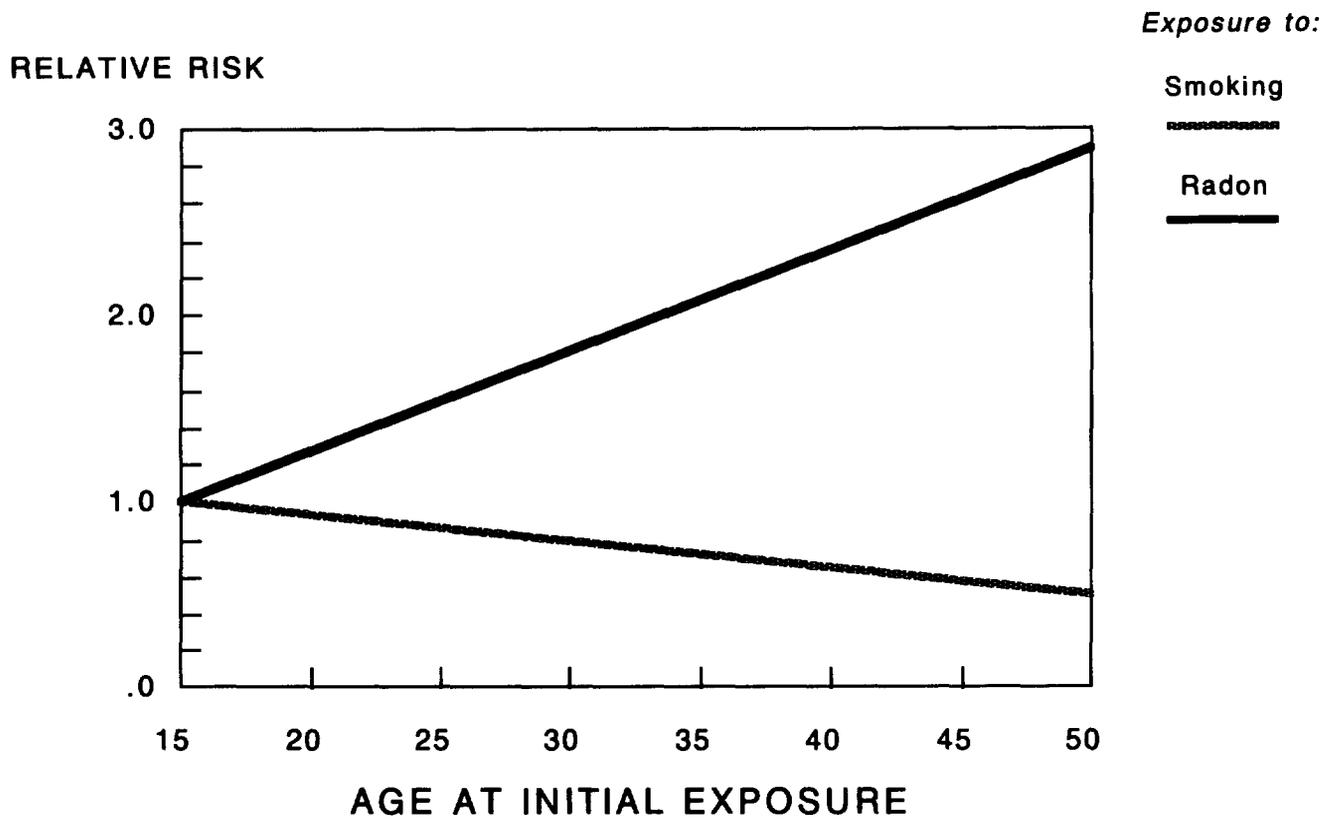


FIGURE 6

EFFECT OF CESSATION OF EXPOSURE ON A MULTISTAGE MODEL

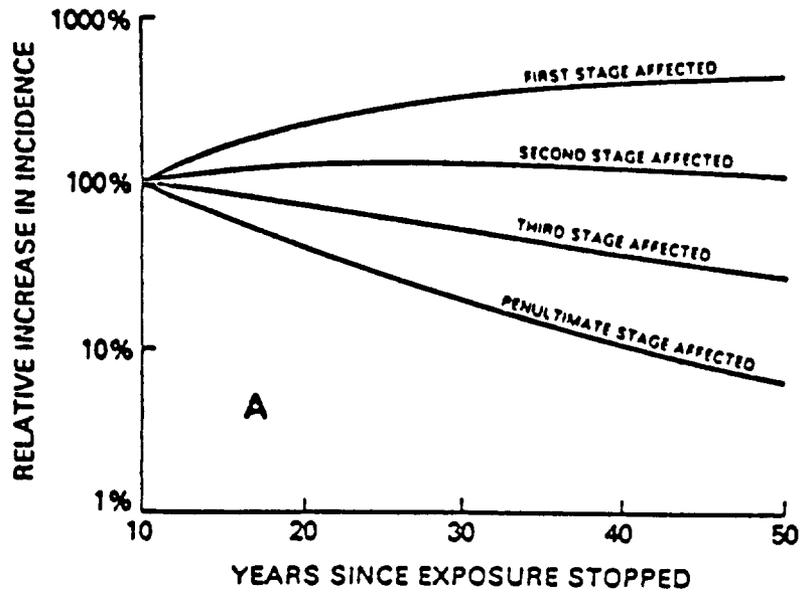
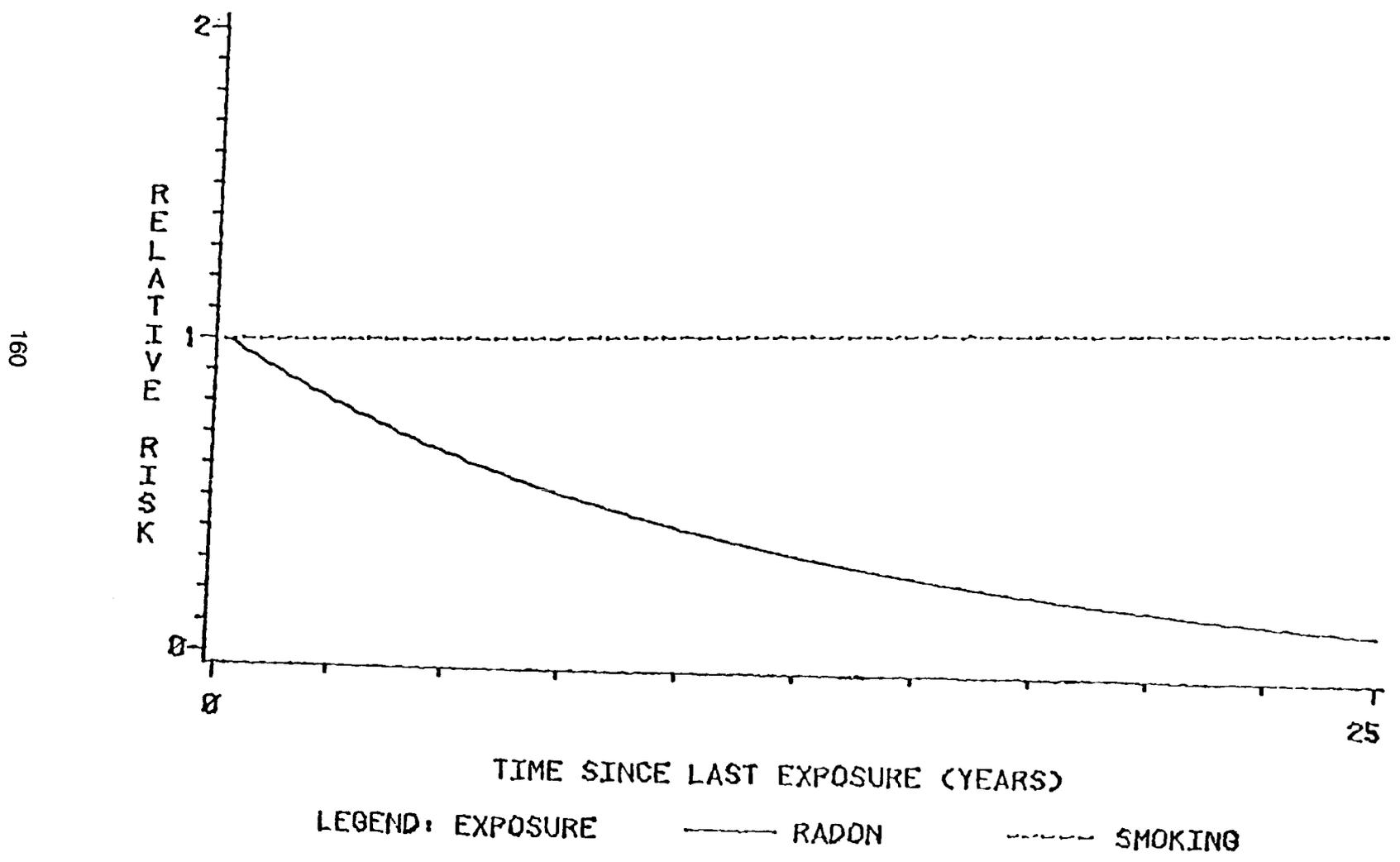


FIGURE 7
EFFECT OF TIME SINCE LAST EXPOSURE ON EXCESS RELATIVE RISK



IV. ERRORS IN EXPOSURE DATA AND THEIR EFFECT UPON RISK ASSESSMENT

In animal carcinogenesis studies, exposures or doses are usually known with a high degree of accuracy and precision. However, the same cannot be said regarding epidemiologic quantitative risk studies. In most epidemiologic studies, the actual dose to target organs can only be estimated by dosimetric modeling. This is seldom attempted in quantitative risk assessments. The dosimetry of radon daughter exposure is very complex, involving such factors as respiration rates, particle size distribution, deposition in the lung, and radon/radon daughter equilibrium. Most risk assessments are modeled as functions of some exposure index, which is the method used in this report. It is the purpose of this section to estimate the magnitude of exposure errors and their effect upon quantitative risk models. According to Lundin et al. [1971], exposures in a given mine and year were estimated in one of four ways:

1. actual measurements
2. interpolation or extrapolation in time
3. geographic area estimation
4. estimates prior to 1950 based upon knowledge of ore bodies, ventilation practices, and earliest measurements.

These methods will subsequently be called Methods 1, 2, 3, and 4. In assessing the error associated with individual exposure determinations, it is first necessary to consider the variability introduced by each of the four methods.

A. Magnitude of Error in Exposure Data

Method 1

Table 5 provides a frequency count of white miners working underground from 1950-68 and the mean number of samples taken in each mine visited in those years. The Kusnetz procedure for measuring radon daughters was most often used during the period of study (Johnson and Schiager 1981). This is an area monitoring method based on alpha counts collected on a filter/pump apparatus. The resulting data were generally thought to be of good quality (Lundin et al., 1971). Data from mines in which 5 or more measurements were taken in a given year were analyzed. These data followed a lognormal distribution with little change over the period 1951-1968. Prior to 1960, samples were taken largely by the U.S. Public Health Service, while post-1960 sampling was conducted by state mine inspectors. Therefore, data were separated into pre and post 1960 periods and estimates of the coefficient of variation (CV) were made for each period. Results indicated a slight but non-significant increase in CV's after 1960 (106.6% vs 118.3%). Since the measurements were grab samples taken at different times within each mine, the total pooled CV=112.5% over the period 1951-1968 is assumed to include sampling errors, counting errors, and environmental fluctuations over time. This estimate agrees well with the CV of 110% found in an independent study of U.S. mines in the period 1973-79 when exposure levels were much lower (Schiager et al. 1981). In other studies, however, an average CV of 30%

Table 5. Number of Miners Exposed and Mean Number of Exposure Measurements Taken by Calendar Year

| Year | Number of Miners Exposed | Mean Number of Samples/Mine |
|------|--------------------------|-----------------------------|
| 1950 | 534 | 1.0 |
| 1951 | 668 | 4.2 |
| 1952 | 748 | 1.6 |
| 1953 | 1028 | 8.5 |
| 1954 | 1376 | 4.3 |
| 1955 | 1383 | 3.8 |
| 1956 | 1572 | 14.2 |
| 1957 | 1942 | 5.6 |
| 1958 | 1798 | 8.8 |
| 1959 | 1861 | 6.6 |
| 1960 | 1902 | 9.9 |
| 1961 | 1588 | 8.8 |
| 1962 | 1369 | 12.9 |
| 1963 | 1005 | 8.4 |
| 1964 | 828 | 15.6 |
| 1965 | 640 | 18.1 |
| 1966 | 467 | 18.5 |
| 1967 | 480 | 21.4 |
| 1968 | 336 | 21.9 |

was reported for area samples in Canadian mines (Makepeace and Stocker 1980) while fluctuations of 20-30% around daily means were found for radon measurements in non-uranium Norwegian mines (Berteig and Stranden 1981).

Method 2

In order to assess the error in interpolating for gaps in sampling of 1 to 3 years, a simulation procedure was used. Mines having the longest periods of continuous annual measurements were identified. Then the even years' averages were omitted and the average of the two adjacent years was substituted. In this way it was possible to compare the observed annual average with the expected average had that year been missing. This strategy was repeated by imposing three year gaps in the data and again using the average of adjacent years to estimate the three intervening years.

The error variance attributable to Method 2 was then calculated by:

$$\sigma^2 = \sum_i \frac{(\log(O_i/E_i))^2}{N-1}$$

where O_i = actual measurements for intervening years

E_i = interpolated values estimated by average of adjacent years.

The resulting CV was 120.8% for 1 year interpolation and 137.3% for 3 year interpolation. Since these results were not significantly different, they were pooled to yield a CV=131.9%.

Method 3

This method used annual mine averages in the same geographic locality to estimate radon daughter levels in mines for which Methods 1 and 2 could not be used. In order to assess the error associated with this method, four of the uranium mining localities with the greatest number of annual measurements were selected. A simulation procedure similar to that used for Method 2 was employed. Annual averages for selected mines in these localities were omitted for 1 to 4 years. The averages for mines in the nearest district were substituted as the expected radon level if the annual average actually had been missing. The error variance was calculated in the same way as Method 2. The resulting CV was 148.6% for this method.

Method 4

No measurements were available in the period prior to 1950. Therefore, the estimates made using knowledge of ore bodies, ventilation, and earliest known measurements in these mines could not be verified. These estimates comprised less than 6% of the 34,120 annual averages used in exposure assessment. In addition, since only 8 percent of the total underground exposure time for the cohort occurred prior to 1950, the influence of these measurements should be minimal. However, since the

error for this method was probably the greatest of the 4 methods used, we estimated the overall CV for Method 4 to be 25% greater than that for Method 3, i.e. CV=186%.

Table 6 shows the number of annual averages for each of the four methods. Actual measurements comprised only about 10% of the data. In order to obtain an overall estimate of the relative error, a weighted average of the CV's for each method was calculated based on the number of determinations for each method. The resulting overall CV=137%.

The error associated with each miner's cumulative exposure can then be calculated using our estimate of the error in each radon daughter level (WL). The total cumulative exposure (WLM) for each miner is obtained from:

$$WLM = \sum_{i,j} (WL_{ij})(UGMON_{ij})$$

where WL_{ij} is the estimated exposure for mine i in year j and $UGMON_{ij}$ is the number of months spent underground in mine i during year j . The variance of WLM assuming independence of WL_{ij} is then:

$$\begin{aligned} \text{Var}(WLM) &= \sum_{i,j} (UGMON_{ij})^2 \text{var}(WL_{ij}) \\ &= \sum_{i,j} (UGMON_{ij})^2 (CV)^2 (WL_{ij})^2 \end{aligned}$$

where CV is the coefficient of variation for the estimated exposure WL_{ij} .

If we substitute our estimate of the overall CV=137% and use total cumulative exposure divided by total months underground ($WLM/TOTMON$) as an estimate of WL_{ij} for each individual miner, the average CV for cumulative exposure (WLM) is 0.97 or a relative standard deviation of 97% of the total WLM for each miner. Since radon daughter measurements were taken in different areas of each mine and often at different times of the day or week, we will assume that the variance in these measurements reflects the variance in exposure levels among individual miners, i.e.

$$\text{Var}(WLM_{ij}) = \sigma_{ijk}^2$$

where σ_{ijk} = variance in exposure measurement for miner k in mine i and year j .

Table 6. Exposure Measurement Errors Due to Four Methods of Estimating Annual Radon Daughter Concentration

| Exposure Assessment Technique | N | Variance of Natural Log (σ^2) | Coefficient of Variation |
|---|-------|--|--------------------------|
| Actual measurements | 3505 | 0.82 | 1.13 |
| Interpolation over time | 5602 | 1.01 | 1.21 |
| Geographic area estimation | 23159 | 1.16 | 1.49 |
| Estimates prior to 1950 (assumed 1.25 x geographic error) | | | 1.86 |

B. Effect on Relative Risk Estimation of Exposure Measurement Errors

There appears to be a general impression that errors in exposure measurements usually cause an underestimation of relative risk. Indeed, Bross [1954] originally demonstrated that if misclassification was equal in two comparison populations, one would tend to underestimate differences in proportions of diseased persons. Keys and Kihlberg [1963] qualified this concept by showing that relative risk is underestimated when misclassification errors are independent of disease and exposure relationships. In general, it has been shown by Copeland et al. [1977] among others, that relative risk estimates are biased too low in the presence of non-differential misclassification (equal misclassification of disease in both exposed and unexposed groups). Little work has been done concerning the effects of errors in continuous measures of exposure upon relative risk estimates obtained from statistical models. It is this situation that is a potential problem to the analysis in this report.

Prentice [1982] introduced a method for dealing with errors in individual exposure measures when using the Cox proportional hazards model. Prentice, and more recently Hornung [1985], have shown that the direction of bias in relative risk estimation depends upon the error distribution and the shape of the exposure-response model. In general, when the variability in individual exposure errors increases with the level of exposure and the relative risk model is supra-linear (curving upward), relative risk will actually be overestimated when exposure errors are ignored. The popular log-linear or exponential risk function is an example of a model which may often overestimate relative risk in the presence of errors whose magnitude increases with increasing levels of cumulative exposure.

As was reported earlier, the log-linear model did not provide the best fit to the data. Instead, the power function model which involved the logarithms of cumulative exposure and cumulative cigarette smoking provided a better fit. The effect upon risk estimates using this model was investigated when errors in exposure are lognormal as indicated in the previous section. Without presenting the statistical details, it is sufficient to say that under these conditions (power function model and lognormal distribution of exposure errors) the effect upon relative risk estimates is negligible. If the exposure measurements were generally higher than those actually experienced by the miners, as mentioned in the 1971 Monograph, relative risk per WLM would be underestimated regardless of the distribution of exposure measurement errors.

In summary, the degree of error in individual exposure measurements was quite high, an estimated CV of 97%. If, however, these individual errors were lognormally distributed about the annual average concentration in each mine, the degree of bias in relative risk estimates generated by the power function model would be minimal. Regardless of the form of the error distribution, the relative risks generated by the exposure-response model would be too low if the exposure measurements were systematically too high. Therefore, examination of the pattern of error in the exposure data would suggest that relative risks produced by the power function model are either unbiased or possibly a bit low.

V. QUANTITATIVE RISK ESTIMATES

The previous sections have outlined the protocol for the risk model development, the selection of an appropriate quantitative risk model, the temporal factors influencing risk estimation, and the magnitude and effect of exposure measurement errors. These are factors requiring careful study before attempting to make valid quantitative risk estimates.

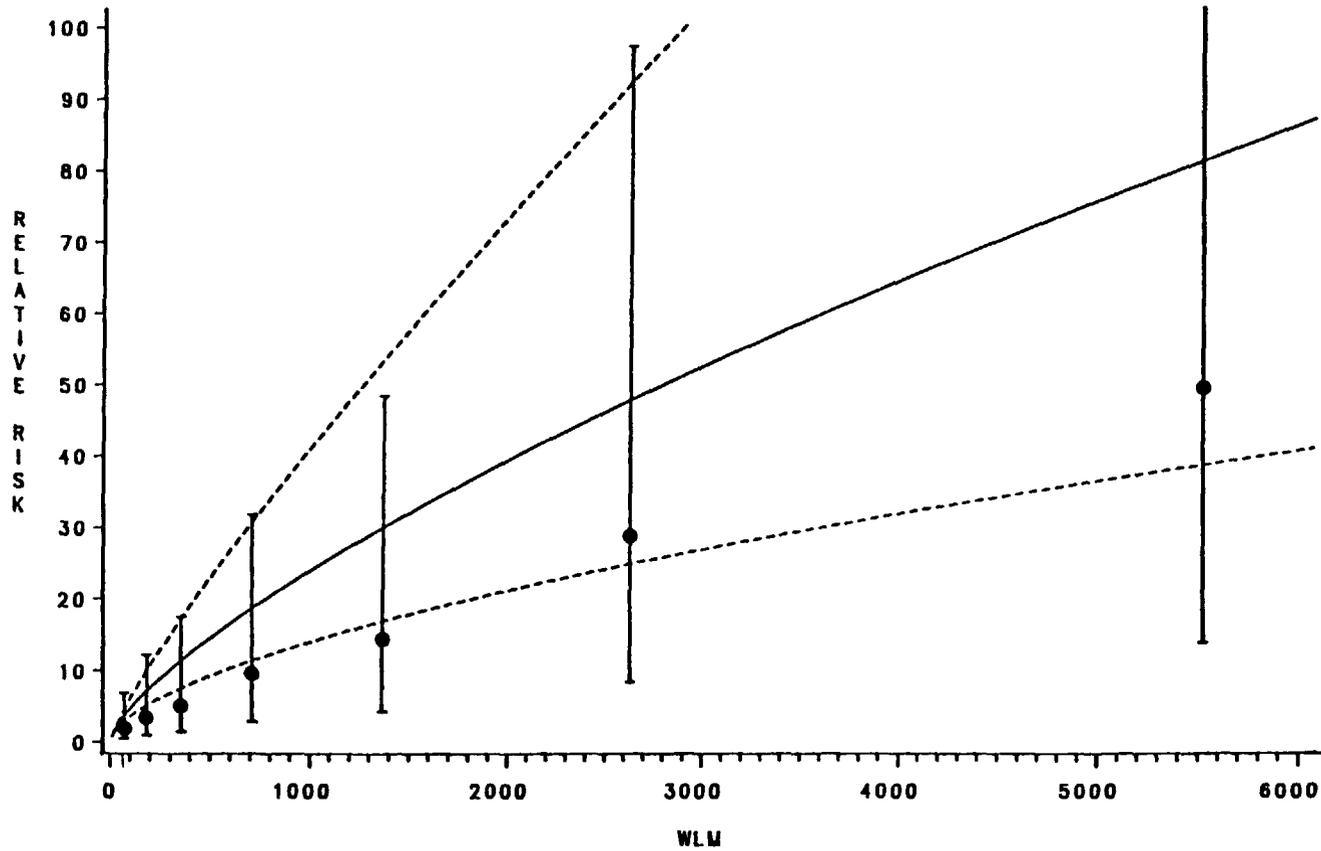
In most risk assessments, results are reported relative to some unexposed population. In animal studies, a control group is generally used for this purpose. In life table, analyses expected mortality is obtained from some standard population, often that of the U.S. The problems inherent with the use of such external referents have been well documented [Enterline 1976]. Although a subcohort of miners unexposed to radon daughters would be ideal for a referent group, there were no unexposed miners in the U.S. cohort. Since the proportional hazards model uses internal comparisons in generating risk estimates, risk projections relative to an unexposed population necessarily involve an extrapolation to zero exposure. In the case of the power function model, a background exposure of 0.2 WLM/year of age was added to every miner's cumulative total. All risk estimates are relative to someone exposed to these background rates. Therefore, quantitative relative risk estimates are somewhat sensitive to the choice of a background exposure rate.

One way of checking the appropriateness of the model is to divide cumulative exposure into discrete intervals and calculate lung cancer risks in each interval relative to risks experienced in the lowest interval. In this way, relative risk estimates are free of any exposure-response function. If the risk model then fits the risk estimates in the selected intervals, one would be assured that the model is appropriate for quantitative risk estimation.

The cumulative exposure intervals chosen for this analysis were: less than 20 WLM, 20-120, 120-240, 240-480, 480-960, 960-1920, 1920-3720, and greater than 3720 WLM. Risk estimates in each interval are calculated relative to the risk in the interval less than 20 WLM, and are plotted at the mean exposure in each interval: 66.6, 179, 351, 698, 1352, 2579, and 5416 WLM, respectively. Figure 8 illustrates how these interval estimates are uniformly lower than those produced by the risk model when using 0.2 WLM/year as a background rate of exposure. The shape of the risk model, however, shows remarkably good agreement with the pattern of relative risk estimates in the selected intervals. This implies that the quantitative risk model is appropriate exclusive of the intercept. This could be due to either an improper choice of baseline exposure rate or the fact that all interval estimates are relative to exposure in the lowest interval, 0-20 WLM. If there is some level of excess risk in this interval relative to an actual unexposed population, the interval estimates would be too low.

The cumulative exposure of 0.2 WLM/year is an estimate is an estimate of the background exposure in the overall U.S. population [NCRP Report No. 77, 1984]. Exposures near ore-bearing lands are known to be considerably higher than average [NCRP Report No. 45, 1975]. Therefore, it is probable that background exposures in the Colorado Plateau area are higher than average U.S. levels.

FIGURE 8
RELATIVE RISK AS A FUNCTION OF CUMULATIVE RADON DAUGHTER EXPOSURE
BACKGROUND EXPOSURE=0.2 WLM/YEAR



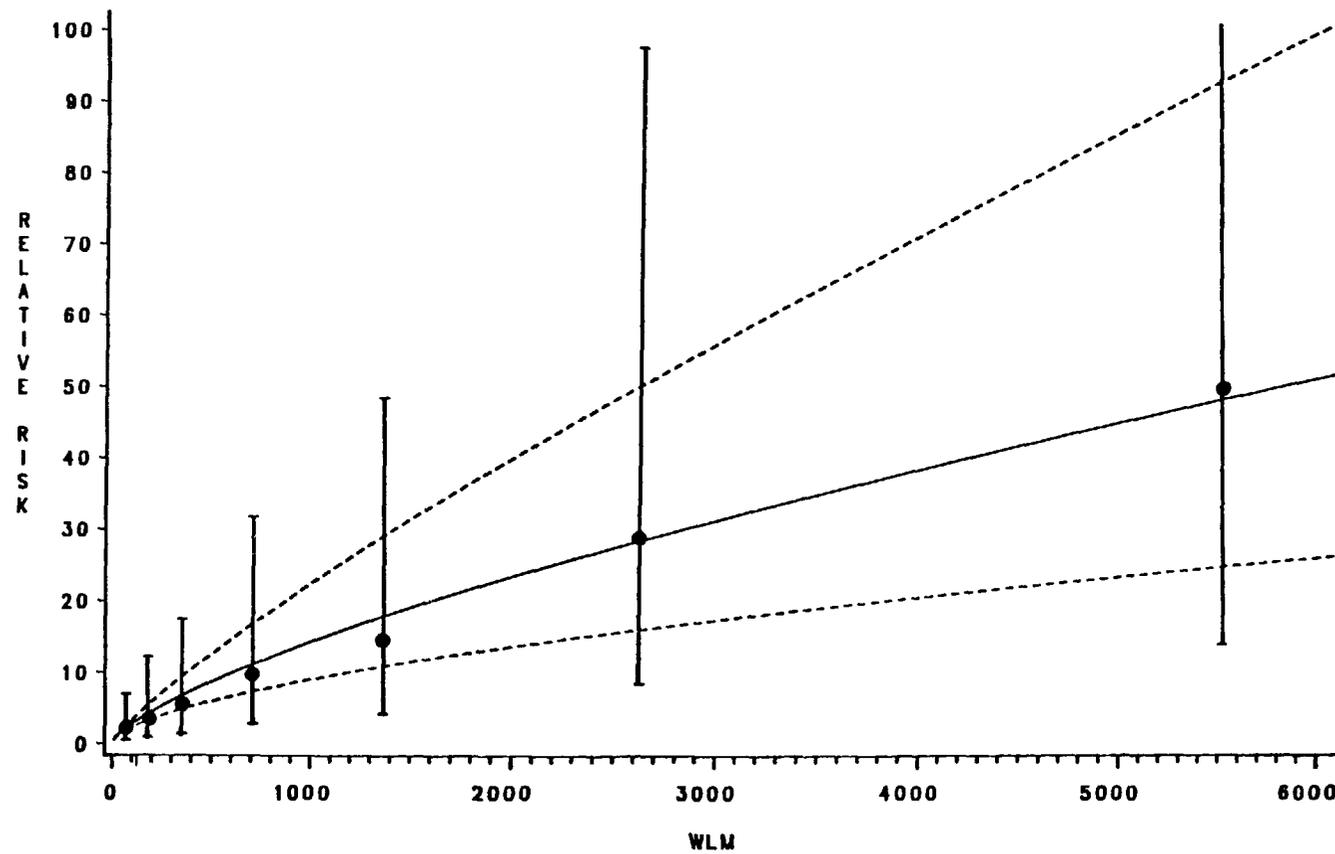
DOTTED LINES AND VERTICAL BARS REPRESENT 95% CONFIDENCE LIMITS

In the interest of using a background more in line with exposures received by persons living in the Colorado Plateau, the background exposure was increased to 0.4 WLM/year. This produced a quantitative risk model that agreed very well with the interval estimates, as can be seen in Figure 9.

Using this model, relative risk estimates were calculated for cumulative radon daughter exposures in the range 30 to 120 WLM corresponding to exposure levels of from one to four WLM/year over a 30-year working lifetime. These estimates range from a relative risk of 1.42 at 30 WLM to 2.07 at 120 WLM compared to someone of the same age and smoking habits with a cumulative lifetime background exposure of 24 WLM and a background exposure rate of 0.4 WLM/year. These estimates (0.9 to 1.4 excess relative risk per 100 WLM) are slightly higher than those reported by Muller et al. [1983] for the Ontario miners, but somewhat less than the estimates of Radford and Renard [1984] for the Swedish iron miners.

Obviously, these estimates are subject to the usual caveats concerning extrapolation from higher cumulative exposures and exposure rates. Because relatively few data are currently available in this cohort below 120 WLM (10 lung cancer deaths out of 709 miners), there may be some doubt that the model used actually is appropriate at these low levels. However, the pattern of relative risk estimates produced in each of the categorized exposure levels would suggest that this model fits the data well in range of 60 to 6000 WLM.

FIGURE 9
RELATIVE RISK AS A FUNCTION OF CUMULATIVE RADON DAUGHTER EXPOSURE
BACKGROUND EXPOSURE=0.4 WLM/YEAR



DOTTED LINES AND VERTICAL BARS REPRESENT 95% CONFIDENCE LIMITS

VI. SUMMARY AND CONCLUSIONS

A valid quantitative risk assessment is much more than simply fitting an exposure-response curve to mortality data. This is especially true when considering an epidemiologic risk assessment. There are a great variety of risk factors and temporal effects that may alter the interpretation of the data analysis. This report is an attempt to address such modifying influences in an effort to better understand the underlying cancer mechanisms operative in the cohort of U.S. uranium miners exposed to radon daughters.

There were a number of findings which are important in assessing the risk of lung cancer in the U.S. cohort.

1. Influence of Cigarette Smoking

The joint effect of cumulative cigarette smoking and cumulative radon daughter exposure was found to be intermediate between additive and multiplicative. This would imply a synergistic relationship in the usual definition as an effect exceeding the sum of the two relative risks.

2. Exposure-Rate Effect

Analysis of this data revealed that modeling cumulative exposure alone may not adequately predict the relative risk of lung cancer from chronic exposure to radon daughters. Miners receiving a given amount of cumulative exposure at lower rates for longer periods of time were at greater risk relative to those with the same cumulative exposure received at higher rates for shorter periods of time. This effect is supported by the convex (decelerating) shape of the exposure-response model which indicates lower exposures are more effective per unit WLM than higher exposures. Though this result may seem somewhat counter-intuitive, it is consistent with a variety of animal carcinogenesis and in vitro cellular studies after treatment with alpha radiation. This implies that results extrapolated from historical exposures at high rates may yield conservative results at current lower rates. Indeed, it is possible that lower risk estimates in the U.S. study, when compared to the four other major radon studies, as reported by Thomas et al. [1985] may be due to the higher exposure rates received by U.S. miners.

3. Late-Stage Carcinogenic Effect

Careful examination of temporal effects implies that exposure to radon daughters acts at a late stage in the carcinogenic process. All temporal factors agreed in this respect. The appropriate lag to remove redundant exposure was a relatively short six years. Older miners at initial exposure were at greater risk than those exposed at younger ages. The relative risk of lung cancer decreases with the length of time after cessation of exposure. Whether or not the mathematical form of the multistage theory of carcinogenesis applies to this cohort, the temporal patterns are worth noting.

4. Magnitude and Effect of Errors in Exposure Measurements

Analyses of the errors associated with the four methods of estimating uranium mine exposure levels indicated a lognormal distribution of errors with the relative standard deviation or CV=97 percent. Although errors of this magnitude may cause overestimation of relative risk when using the log-linear risk model, the better-fitting power function model is generally insensitive to errors of this type. In fact, if estimated exposure levels were systematically higher than those actually received by the miners [Lundin et al. 1971], relative risks per unit WLM would be underestimated for this data.

5. Quantitative Risk Estimates

Present day radon daughter exposures are considerably less than those experienced in the past by uranium miners. There is also current interest in low-level exposure to the general population from indoor radon and its decay products. Consequently, the primary cumulative exposure range of interest in risk assessment appears to be below 120 WLM. Although approximately 20 percent of the cumulative exposures in this study were below this level, there have been only 10 lung cancer deaths among this subgroup as of the end of 1982. Until this cohort is followed to extinction, epidemiologic models such as that produced in this report will be necessary to evaluate the risk of lung cancer mortality at these lower exposures.

The model developed for this report provides a very good fit to the data in the range 60 to 6000 WLM. It seems reasonable that predictions based upon this model would be reliable at least for occupational exposure to adult white males. There is little or no mortality data available regarding women and children. The risk estimates provided in Table 7 are presented as an evaluation based upon careful consideration of all factors thought to influence such long-term mortality studies. All of the caveats associated with such evaluations apply to some degree to these results.

Table 7. Quantitative Risk Estimates of Lung Cancer at Four Exposure Rates Over a Thirty Year Working Lifetime

| Exposure Rate | Cumulative Exposure (30 Years) ¹ | Relative Risk ² | 95% Confidence Limits |
|---------------|---|----------------------------|-----------------------|
| 1 WLM/year | 30 WLM | 1.42 | 1.18 - 1.72 |
| 2 WLM/year | 60 WLM | 1.66 | 1.22 - 2.26 |
| 3 WLM/year | 90 WLM | 1.88 | 1.28 - 2.76 |
| 4 WLM/year | 120 WLM | 2.07 | 1.33 - 3.22 |

¹Exclusive of background exposure.

²Risks are calculated using exposure rate interaction model in Table 6 relative to miners of the same age and smoking habits with a cumulative lifetime background exposure of 24 WLM and background exposure rate of 0.4 WLM/year.

LIST OF REFERENCES

1. Armitage, P., and Doll, R. [1961]. Stochastic Models for Carcinogenesis, Proceedings of Fourth Berkeley Symposium on Mathematical Statistics and Probability 4, University of California Press, 19-38.
2. Berteig, L., and Stranden, E. [1981]. Radon and Radon Daughters in Mine Atmospheres and Influencing Factors, In: M. Gomez, ed. Radiation Hazards in Mining. American Institute of Mining, Metallurgical and Petroleum Engineering, Inc., New York, 89-94.
3. Bross, I. [1954]. Misclassification in 2 x 2 Tables, Biometrics 10, 478-486.
4. Brown, C.C., and Chu, K.C. [1983]. Implications of the Multistage Theory of Carcinogenesis Applied to Occupational Arsenic Exposure JNCI 70, 455-463.
5. Chameaud, J., Perraud, R., Masse, R., and Lafuma, J. [1981]. Contribution of Animal Experimentation to the Interpretation of Human Epidemiological Data, In: M. Gomez, ed. Radiation Hazards in Mining. American Institute of Mining, Metallurgical and Petroleum Engineering, Inc., New York, 222-227.
6. Copeland, K.T., Checkoway, H., McMichael, A.J., and Holbrook, R.H. [1977]. Bias Due to Misclassification in the Estimation of Relative Risk, American Journal of Epidemiology 105, 488-495.
7. Cox, D.R. [1972]. Regression Models and Life Tables, Journal of the Royal Statistical Society, Series B 34, 187-202.
8. Cross, F.T., Palmer, R.F., Dagle, G.E., Busch, R.H., and Buschbom, R.L. [1980]. Influence of Radon Daughter Exposure Rate, Unattachment Fraction, and Disequilibrium on Occurrence of Lung Tumours, Radiation Protection Dosimetry 7, 381-384.
9. Day, N.E., and Brown, C.C. [1980]. Multistage Models and Primary Prevention of Cancer, Journal of the National Cancer Institute 64, 977-989.
10. Doll, R. and Peto, R. [1978]. Cigarette Smoking and Bronchial Carcinoma: Dose and Time Relationships Among Regular Smokers and Life-Long Non-Smokers, Journal of Epidemiology and Community Health 32, 303-313.
11. Enterline, P.E. [1976]. Pitfalls in Epidemiologic Research: An Examination of the Asbestos Literature, Journal of Occupational Medicine, 18, 150-156.

12. Hill, C.K., Buonaguro, F.M., Myers, D.P., Han, A. and Elkind, M.M. [1982]. Fission-Spectrum Neutrons at Reduced Dose Rates Enhance Neoplastic Transformation, *Nature*, Vol. 298, 67-69.
13. Hinds, W.C., and First, M.W. [1975]. Concentrations of Nicotine and Tobacco Smoke in Public Places, *New England Journal of Medicine* 292, 844-845.
14. Hornung, R.W. [1985]. Modeling Occupational Mortality Data with Applications to U.S. Uranium Miners, Doctoral Dissertation, Dept. of Biostatistics, School of Public Health, University of North Carolina.
15. Keys, A. and Kihlberg, J.K. [1963]. Effects of Misclassification on Estimated Relative Prevalence of a Characteristic, *American Journal of Public Health* 53, 1656-1665.
16. Land, E. [1976]. Presentation for 1976 OSHA Hearings on Coke Ovens.
17. Lundin, F.E., Archer, V.E., and Wagoner, J.K. [1979]. An Exposure-Time-Response Model for Lung Cancer Mortality in Uranium Miners: Effects of Radiation Exposure, Age, and Cigarette Smoking, Energy and Health, Breslow and Whittemore (eds.) SIAM, Philadelphia, 243-264.
18. Lundin, F.E., Wagoner, J.K. and Archer, V.E. [1971]. Radon Daughter Exposure and Respiratory Cancer Quantitative and Temporal Aspects, NIOSH-NIEHS Joint Monograph No. 1. Feigl, P. and Zelen, M. [1965]. Estimation of Exponential Survival Probabilities with Concomitant Information, *Biometrics* 21, 826-838.
19. Makepeace, C.E., and Stocker, H. [1980]. Statistical interpretation of a Frequency of Monitoring Program Designed for the Protection of Underground Uranium Miners from Overexposure to Radon Daughters, *The Canadian Mining and Metallurgical Bulletin* 73, 113-124.
20. Mancuso, T.F., Steward, A., and Kneale, G. [1977]. Radiation Exposures of Hanford Workers Dying from Cancer and Other Causes, *Health Physics* 33, 369-385.
21. Muller, H.G. [1951]. Radiation Damage to the Genetic Material. *Science Program* 7, 93-493.
22. Muller, J., Wheeler, W.C., Gentleman, J.F., Suranyi, G. and Kusiak, P.A. [1983]. Study of Mortality of Ontario Miners, 1955-1977, Part I. Ontario Ministry of Labor.
23. National Council on Radiation Protection and Measurements [1975]. Natural Background Radiation in the United States, NCRP Report No. 45, Washington, D.C.
24. National Council on Radiation Protection and Measurements [1984]. Exposures from the Uranium Series with Emphasis on Radon and its Daughters, NCRP Report No. 77, Washington, D.C.

25. Nordling, C.O. [1953]. A New Theory of the Cancer Inducing Mechanism, *British Journal of Cancer*, 7, 68-72.
26. Prentice, R.L. [1982]. Covariate Measurement Errors and Parameter Estimation in a Failure Time Regression Model, *Biometrika* 69, 331-342.
27. Raabe, O.G., Book, S.A., Parks, N.J. [1983]. Lifetime Bone Cancer Dose-Response Relationships in Beagles and People from Skeletal Burdens of 226 Ra and 90 Sr Health Physics Vol. 44 Supplement No. 1, 33-48.
28. Radford, E.P. and Renard, K.G.S.C. [1984]. Lung Cancer in Swedish Iron Miners Exposed to Low Doses of Radon Daughters, *New England Journal of Medicine* 310, 1485-1494.
29. Schiager, K.J., Johnson, J.A., and Borak, T.B. [1981]. Radiation Monitoring Priorities for Uranium Miners, in *Radiation Hazards in Mining*, M. Gomez (ed.) American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York 738-745.
30. Thomas, D.C., McNeill, K.G., and Daugherty, C. [1985]. Estimates of Lifetime Lung Cancer Risks Resulting from Radon Daughter Exposure, *Health Physics*, in press.
31. Whittemore, A.S. [1977]. The Age Distribution of Human Cancer for Carcinogenic Exposures of Varying Intensity, *American Journal of Epidemiology* 106, 418-432.
32. Whittemore, A.S. and McMillan, A. [1983]. Lung Cancer Mortality Among U.S. Uranium Miners: A reappraisal, *Journal of the National Cancer Institute* 71, 489-499.

APPENDIX III

ENGINEERING CONTROL METHODS

A. Introduction

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

B. Mechanical Ventilation

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

1. General Principles

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

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

To prevent mixing fresh air and contaminated air in the shaft or drift leading to the dead end, the secondary system usually consists of ductwork with a fan to blow or exhaust fresh air from the main passageway to the face. The contaminated air then passively returns to

the main passageway (because of a pressure gradient) through the shaft without contaminating the supply air. The contaminated air at the stope may also be brought back to the main passageway through a second duct and fan system. Once returned to the main passageway, the contaminated air joins the primary exhaust air stream which is then carried out of the mine.

2. Designing a Dilution Ventilation System

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

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

3. Primary Ventilation System

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

a. Split or Parallel Ventilation Systems

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

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

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

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

b. Control Devices

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

c. Pushing Versus Pulling Ventilation Systems

The pressure on the air intake side of a mine is always greater than on the exhaust side regardless of whether a pushing or pulling ventilation system is used. The difference is that the intake side

pressure is greater than atmospheric pressure for a pushing system, whereas in an exhaust or pulling system, the pressure on the intake side is below atmospheric pressure.

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

4. Secondary (Auxiliary) Ventilation System

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

a. Use of Ducts

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

b. Blowing Duct System (Push System)

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

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

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

the ventilated areas when an air-blowing system was utilized than when an exhaust system was used.

c. Exhaust Duct System (Pull System)

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

- Fresh incoming air is maintained in the tunnel used by miners to access the active stope, and
- The contaminated air within 10 feet of the duct is very effectively removed from the work area

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

d. Push-Pull System

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

- The blowing of air that sweeps across and ventilates the active face, thus providing good dilution in work areas;
- The efficient collection of contaminants near the work face; and
- Reducing the contamination of air in the access tunnel.

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

5. Overpressurization and Mine Pumping

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

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

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

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

6. Fan Operation

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

C. Bulkheads

1. Description

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

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

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

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

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

The third part of the bulkhead, the seal on the surface of the rock within one meter from the plane of the bulkhead, must be made of a material that adheres to damp rock surfaces and can withstand mining

activities. Summers et al. [1982] tested the efficacy of this procedure and found that the amount of radon gas escaping through the surrounding rock was insufficient to warrant the uniform use of a wall sealant, provided that all cracks, fissures, and holes were sealed to prevent major leaks.

2. Membrane Sealants Used on Bulkheads

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

3. Negative Air Pressure Behind a Bulkhead

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

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

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

4. Efficiency

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

estimate that 100 bulkheads sealing 12.5 stopes would reduce the overall radon gas emissions into mine air by 2.25 Ci/day, a reduction of 25%.

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

D. Backfilling

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

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

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

Although backfilling can produce transient increases in radon gas, it can also be efficacious in reducing overall radon progeny emissions from a mine [Bloomster et al. 1984b; Franklin 1981]. As currently practiced, backfilling can reduce the ventilation volume of a stope by 90% or more. During experiments in a mine, Franklin et al. [1981] found that backfilling 90% of a stope reduced the total radon progeny emissions from the stope by 85%. A feasibility study estimated that backfilling can be as effective as

bulkheading in reducing overall radon progeny emissions; however, the cost is much higher [Bloomster et al. 1984b]. Two field studies [Franklin et al. 1982; Raghavayya and Khan 1973] reported extremely high emanation rates from cemented or sand backfill; however, in both instances the backfill was wet; these studies did not report the efficacy of the backfill after it dried.

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

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

E. Sealants Used on Mine Walls

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

1. Description

a. Sealant Application Methods

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

b. Sealant Materials

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

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

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

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

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

Edwards and Bates [1980] of the Bureau of Mines developed a computer model to evaluate the effect of pinholes in an otherwise impermeable sealant. They concluded that pinholes (2 mm in diameter) were not a

problem unless there were several thousand visible pinholes per square meter of sealant.

2. Effectiveness of Sealants in Reducing Radon Emanation Rates

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

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

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

F. Controlling Radioactive Water Underground

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

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

G. Automation

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

REFERENCES

- ACGIH [1984]. Industrial ventilation--A manual of recommended practice. 18th edition. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.
- Bates RC, Franklin JC [1977]. U.S. Bureau of Mines radiation control research. Proceedings of the Conference on Uranium Mining Technology, Reno NV, April 25-29.
- Bloomster CH, Enderlin WI, Young JK, Dirks JA [1984a]. Cost survey for radon daughter control by ventilation and other control techniques. Volume I. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152932.
- Bloomster CH, Jackson PO, Dirks JA, Reis JW [1984b]. Cost survey for radon daughter control by ventilation and other control techniques: radon emissions from underground uranium mines. Volume II. Richland, WA: Battelle Memorial Institute, Pacific Northwest Laboratories, NTIS PB85-152940.
- Bossard FC, LeFever JJ, LeFever JB, Stout KS [1983]. A manual of mine ventilation design practices. Second edition. Butte, MT: Floyd C. Bossard and Associates, Inc.
- Cooper WE [1981]. A comparison of radon-daughter exposures calculated for U.S. underground uranium miners based on MSHA and company records. In: Gomez M, ed. International Conference: Radiation Hazards in Mining, New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 292-295.
- Edwards JC, Bates RC [1980]. Theoretical evaluation of radon emanation under a variety of conditions. Health Phys 39:263-274.
- Ferdinand FW, Cleveland JE [1984]. Philosophies and practices in radiation monitoring and exposure calculations in modern uranium mines. Unpublished report submitted to the National Institute for Occupational Safety and Health by the Quivira Mining Company.
- Franklin JC [1981]. Control of radiation hazards in underground uranium mines. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 441-446.
- Franklin JC, Bates RC, Habberstad JL [1975a]. Polymeric sealants may provide effective barriers to radon gas in uranium mines. E/MJ, September 1975, pp. 116-118.
- Franklin JC, Nuzum LT, Hill AL [1975b]. Polymeric materials for sealing radon gas into the walls of uranium mines. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8036.

- Franklin JC, Meyer TO, Bates RC [1977]. Barriers for radon in uranium mines. U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8259.
- Franklin JC, Meyer TO, McKibbin RW, Kerkering JC [1978]. A continuous radon survey in an active uranium mine. Mining Engineering, pp. 647-649.
- Franklin JC, Musulin CS, Bates RC [1980]. Monitoring and control of radon hazards. Proceedings of the Second International Mine Ventilation Congress, Reno, NV, pp. 405-411.
- Franklin JC, Weverstad KD, Black JW, Cleveland JE [1981]. Radiation hazards in backfilling with classified uranium mill tailings. Fifth Annual Cent. New Mexico AIME Uranium Seminar, Albuquerque, NM.
- Franklin JC, Washington RA, Kerkering JC, Montone H, Regan R [1982]. Radiation emanation from stopes backfilled with cemented uranium mill tailings. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8664.
- Kown BT, Van der Mast VC, Ludwig KL [1980]. Technical assessment of radon-222 control technology for underground uranium mines. Washington, DC: U.S. Environmental Protection Agency, Office of Radiation Programs (ANR-458). Technical Note ORP/TAD-80-7, Contract No. 68-02-2616, Task No. 9.
- Lindsay DB, Oberholtzer JE, Summers CH [1981a]. Sealant tests to control radon emanation in a uranium mine. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report No. 83836.
- Lindsay DB, Schroeder GL, Summers CH [1981b]. Polymeric wall sealant test for radon control in a uranium mine. In: Gomez M, ed. International Conference: Radiation Hazards in Mining. New York, NY: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., pp. 790-793.
- Lundin FE, Wagoner JK, Archer VE [1971]. Radon daughter exposure and respiratory cancer: quantitative and temporal aspects. U.S. Department of Health, Education, and Welfare, Public Health Service, National Institute for Occupational Safety and Health, National Institute of Environmental Health Sciences, Joint Monograph No. 1.
- Musulin CS, Franklin JC, Roberts FA [1982]. Effects of a fan shutdown on radon concentration in a positive pressure ventilated mine. Washington, DC: U.S. Department of the Interior, Bureau of Mines, Report of Investigations 8738.
- Ragavayya M, Khan AH [1973]. Radon emanation from uranium mill tailings used as backfill in mines. In: Stanley RE and Moghissi AA, eds. Noble Gases. Las Vegas, NV: U.S. Environmental Protection Agency, National Environmental Resource Center, Office of Research and Development, EPA 600/9-76-026, pp. 269-273.

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

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

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

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

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

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

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

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

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

APPENDIX IV

GRAB SAMPLING STRATEGY REQUIREMENTS FOR DETERMINATION OF RADON PROGENY EXPOSURES

A. Introduction

Airborne concentrations of radon progeny must be monitored regularly to provide the basis for their control. Miners' exposures must be limited to no more than 1.0 WLM per year and the average concentration of radon progeny in any work area must not exceed 1/12 WL during any work shift. The sampling strategy described here was developed after an evaluation of mine sampling data and the typical variability of radon progeny concentrations in underground mines. This strategy will allow the collection of timely and reliable environmental data that can be used as the basis for control of cumulative exposures. This sampling strategy allows for the determination of the arithmetic average of time-varying concentrations of radon progeny during a work shift in a given work area. The determination is based on an unbiased estimate made from grab samples taken at random intervals throughout the work shift. Random sampling of work shifts during a reference period is also included for determination of a long-term arithmetic average work shift concentration. The formulae needed to calculate the statistical quantities used in this sampling strategy are contained in section G of this appendix. The rationale for the critical decision points used in the sampling strategy are contained in section H.

B. Definition of Terms and Notations

STATION: A sampling location within a work area that represents the radon progeny concentration to which miners are exposed.

CLUSTER: Two or more stations at which sampling will be conducted during any work shift. The stations in a cluster should be located at different work areas but must be in close proximity to each other so that alternating grab samples could be taken during the same work shift.

BLOCK OF TIME: A period in which two different sampling days are randomly selected.

AVERAGE WORK SHIFT CONCENTRATION: The average concentration of radon progeny in working levels (WL) during a work shift at a given station.

AVERAGE: The arithmetic mean. The same term can be used for the average of several sample results or for the arithmetic mean of a distribution of concentrations that vary during a continuous period of time. In the latter case, the terms "average," "arithmetic average," and "time-weighted average" are synonymous.

- α_i : Average work shift concentration for day i , where $i = 1, 2, \dots, 12$ and day i is the i th day in a time-ordered sequence of the 12 days that were randomly selected from the reference period.
- $\hat{\alpha}_i$: Estimate of α_i (based on seven grab samples), where $i = 1, 2, \dots, 12$ and day i is the i th day in a time-ordered sequence of the 12 days that were randomly selected from the reference period.
- $\hat{\alpha}_{i+1}$: Estimated average work shift concentration for day $i+1$ (based on seven grab samples), where $i = 1, 2, \dots, 11$ and day $i+1$ is the next sampling day following day i in a time-ordered sequence of the 12 days that were randomly selected from the reference period.
- $\hat{\alpha}_A$: Estimated average work shift concentration for day A (based on seven grab samples), where "day A" is a term used to designate one of the 12 randomly selected days sampled during the reference period for which the α_i value is in a critical range.
- $\hat{\alpha}_B$: Estimated average work shift concentration for day B (based on seven grab samples), where day B is the first workday following day A. [Note: Day B may or may not be the next calendar day after day A since a weekend, holiday, or other non-workday may occur between days A and B.]
- α_{\bullet} : Long-term average work shift concentration during a reference period from which 12 sampling days were randomly selected.
- $\hat{\alpha}_{\bullet}$: Estimated long-term average work shift concentration (based on seven grab samples per sampling day) during the reference period from which 12 sampling days were randomly selected.
- $\hat{\alpha}_{11}$: Estimated average work shift concentration (based on seven grab samples) on the 11th of the 12 randomly selected days sampled during the reference period.
- $\hat{\alpha}_{12}$: Estimated average work shift concentration (based on seven grab samples) on the last of the 12 randomly selected days sampled during the reference period.
- LCL: 95% one-sided lower confidence limit for α_{\bullet} .
- UCL: 95% one-sided upper confidence limit for α_{\bullet} .

C. Requirements for Routine Exposure Monitoring

1. Two different sampling days are randomly selected from each 2-week block of time.
2. The stations within a cluster are to be sampled on the same workdays and work shifts. All stations within a cluster are to be alternately sampled, seven times on each sampling day, each time in independent random order. During the work shift, the seven periods for sampling of the entire cluster shall be equally spaced in time. For example, the three stations A, B, and C could be considered a cluster and sampled as ABC, BCA, ACB, CBA, CAB, BAC, and ACB during seven successive intervals of approximately equal durations. If it is not feasible to sample in this manner, then sampling can be conducted along the most efficient path but with a different, randomly determined starting point on each day (e.g., BCA, BCA, ..., BCA during one sampling day and ABC, ABC, ..., ABC or CAB, CAB, ..., CAB during other sampling days).
3. The estimated average work shift concentration ($\hat{\alpha}_i$) for each sampling day ($i = 1, 2, \dots, 12$) is computed from an analysis of the seven grab samples taken on that day. Formulae for this computation are contained in section G.
4. Whenever $\hat{\alpha}_i$ for a particular station exceeds 0.14 WL, then that station shall be resampled the next workday. [Note: In this case, $\hat{\alpha}_i = \hat{\alpha}_A$, and sampling on the "next workday" (day B) is in addition to the two randomly selected sampling days required in a 2-week block of time.]
 - a. If $\hat{\alpha}_B$ (the estimated average work shift concentration on the next workday) is ≤ 0.14 WL, then exposure monitoring shall continue as described starting at section C,1.
 - b. If $\hat{\alpha}_B$ also exceeds 0.14 WL, then: (1) steps shall be taken to reduce the radon progeny concentration in that work area by implementing work practices and engineering controls, (2) respiratory protection shall be required for all miners entering that work area, and (3) grab sampling as described in section C,2 shall be conducted on a consecutive daily basis.

Grab sampling shall continue on a consecutive daily basis until the estimated average work shift concentrations on any two consecutive workdays ($\hat{\alpha}_A$ and $\hat{\alpha}_B$) are both ≤ 0.10 WL. When $\hat{\alpha}_A$ and $\hat{\alpha}_B$ are both ≤ 0.10 WL, then the requirements for respiratory protection are waived and exposure monitoring can revert to the schedule described starting at section C,1. [Note: A new reference period shall begin at this time, requiring 12 randomly selected sampling days, the first of which is to be coded as $i = 1$.] This criterion (as discussed in section H,2) serves to provide early confirmation that the corrective steps taken by the mine operator have been effective in limiting the average work shift concentration of radon progeny to a level not exceeding 1.5 times the recommended exposure limit (REL) of 1/12 WL.

5. If \hat{Q}_i is ≤ 0.14 WL, then: (a) continue collecting seven grab samples on each of the two randomly selected sampling days in each 2-week block of time, and (b) continue using the criteria given in section C. After 12 weeks of sampling in which no two consecutive sampling days (\hat{Q}_i and \hat{Q}_{i+1}) were in excess of 0.14 WL, use the criteria given in section D for assurance, based on 12 days of sampling, that the average work shift concentration of radon progeny is in compliance with the REL, which, if verified, will result in less frequent exposure monitoring requirements.

D. Criteria for Less Frequent Exposure Monitoring

To determine if less frequent exposure monitoring can be conducted at a specific work area, the following statistical decision criteria must be used:

1. Compute \hat{Q}_0 (the estimated average work shift concentration using seven grab samples per sampling day) for a work area during the reference period in which 12 samples were taken and no two consecutive sampling days (\hat{Q}_i and \hat{Q}_{i+1}) were in excess of 0.14 WL. Formulae for this computation are contained in section G.
2. Compute LCL and UCL, the 95% one-sided lower and 95% one-sided upper confidence limits, respectively, for the average work shift concentration during the reference period from which the 12 sampling days were taken. Formulae for these computations are contained in section G; \hat{Q}_0 from section D,1 is a quantity used in the formulae for LCL and UCL.
3. The block length can be increased from 2 weeks to 26 weeks (therefore requiring only 2 randomly selected sampling days per 26-week block of time) if both of the following results occur at a station: (a) UCL (for the average work shift concentration during the 12-week period) is $\leq 1/12$ WL, and (b) the estimated average work shift concentrations on any two consecutive randomly selected sampling days (\hat{Q}_i and \hat{Q}_{i+1}) within the same reference period did not exceed 0.14 WL. Criteria for the continuation of less frequent exposure monitoring and for the cessation of exposure monitoring are given in parts E and F, respectively.
4. If LCL exceeds $1/12$ WL, then: (a) steps shall be taken to reduce the radon progeny concentration in that work area by implementing work practices and engineering controls, (b) respiratory protection shall be required for all miners entering that work area, and (c) grab sampling as described in section C,2 shall be conducted on a consecutive daily basis.

Grab sampling shall continue on a consecutive daily basis until the estimated average work shift concentrations on any two consecutive workdays (\hat{Q}_A and \hat{Q}_B) are both ≤ 0.10 WL. When \hat{Q}_A and \hat{Q}_B are both ≤ 0.10 WL, then the requirements for respiratory protection are waived and exposure monitoring can revert to the schedule described starting at section C,1. [Note: A new reference period shall begin at this time, requiring 12 randomly selected sampling days, the first of which is to be coded as $i = 1$.]

E. Criteria for Continuation of Less Frequent Exposure Monitoring

After completion of two additional sampling days during the subsequent 26-week period, the data from the last 12 days sampled must be used to compute a new UCL for the period in which the 12 sampling days occurred.

1. Sampling may continue under the less frequent sampling schedule (i.e., 2 days per 26-week block of time) if both of the following results occur at a station: (a) UCL for the reference period from which the last 12 sampling days were taken is $\leq 1/12$ WL, and (b) the estimated average work shift concentrations on the last two of the 12 sampling days ($\hat{\alpha}_{11}$ and $\hat{\alpha}_{12}$) were both ≤ 0.14 WL. In this case, an updated UCL shall be recomputed after completion of sampling in each subsequent 26-week block of time to determine if less frequent sampling (i.e., on two days during a 26-week period) should be continued according to the criteria of this part. If either of these conditions are not met, then LCL must be computed from data obtained from the last 12 days sampled (see section E,2 which follows).

2. If LCL for the reference period from which the 12 sampling days were taken at a station exceeds $1/12$ WL, then: (a) steps shall be taken to reduce the radon progeny concentration in that work area by implementing work practices and engineering controls, (b) respiratory protection shall be required for all miners entering that work area, and (c) grab sampling as described in section C,2 shall be conducted on a consecutive daily basis.

Grab sampling shall continue on a consecutive daily basis until the estimated average work shift concentrations on any two consecutive workdays ($\hat{\alpha}_A$ and $\hat{\alpha}_B$) are both ≤ 0.10 WL. When $\hat{\alpha}_A$ and $\hat{\alpha}_B$ are both ≤ 0.10 WL, then the requirements for respiratory protection are waived and exposure monitoring can revert to the schedule described starting at section C,1.

3. If LCL for the reference period from which the 12 sampling days were randomly taken is $\leq 1/12$ WL, but the estimated average work shift concentration determined for either of the last two of the 12 sampling days ($\hat{\alpha}_{11}$ or $\hat{\alpha}_{12}$) exceeds 0.14 WL, then monitoring at that station shall return to the more frequent sampling schedule (2 days per 2-week block of time). In this case, $\hat{\alpha}_{11}$ or $\hat{\alpha}_{12}$ becomes $\hat{\alpha}_A$ and sampling is required on the next workday to obtain $\hat{\alpha}_B$, as described starting at section C,4,a.

F. Criteria for Cessation of Exposure Monitoring

Sampling can be discontinued at a station if both of the following results occur at that station: (1) UCL for the reference period from which 12 sampling days were taken is ≤ 0.063 WL, and (2) the estimated average work shift concentration for the last of the 12 sampling days ($\hat{\alpha}_{12}$) is ≤ 0.033 WL. However, sampling should return to the regular schedule, as described starting at section C,1 if an environmental change or a change in mining operations occurs that may alter radon progeny concentrations in that work area.

G. Statistical Considerations and Data Analysis Formulae

The following are the statistical notations used in the sampling strategy:

c_{ij} = measured concentration of radon progeny in the j th grab sample taken on the i th sampling day, where $j = \overline{1,2,\dots,7}$ for each day and $i = \overline{1,2,\dots,12}$ (2 workdays selected at random from each of six consecutive blocks of time).

c_{Aj} = measured concentration of radon progeny in the j th grab sample taken on day A, where $j = \overline{1,2,\dots,7}$.

c_{Bj} = measured concentration of radon progeny in the j th grab sample taken on the next workday following day A, where $j = \overline{1,2,\dots,7}$.

x_{ij} = natural logarithm of $c_{ij} = \ln c_{ij}$

x_{Aj} = natural logarithm of $c_{Aj} = \ln c_{Aj}$

x_{Bj} = natural logarithm of $c_{Bj} = \ln c_{Bj}$

\bar{x}_i = average of the 7 x_{ij} values for the 7 grab samples taken on day i .
 $= (1/7) \sum_{j=1}^7 x_{ij}$

\bar{x}_\bullet = average of the 12 \bar{x}_i values during the reference period from which 12 sampling days were randomly selected.
 $= (1/12) \sum_{i=1}^{12} \bar{x}_i$

\bar{x}_A = average of the 7 x_{Aj} values for the 7 grab samples taken on day A.
 $= (1/7) \sum_{j=1}^7 x_{Aj}$

\bar{x}_B = average of the 7 x_{Bj} values for the 7 grab samples taken on day B, where day B is the next workday following day A.
 $= (1/7) \sum_{j=1}^7 x_{Bj}$

\bar{x}_{11} = average of the 7 $x_{11,j}$ values (natural logarithms) for the 7 grab samples taken on the 11th of the 12 randomly selected sampling days in the reference period.
 $= (1/7) \sum_{j=1}^7 x_{11,j}$

- \bar{x}_{12} = average of the 7 $x_{12,j}$ values (natural logarithms) for the 7 grab samples taken on the last of the 12 randomly selected sampling days in the reference period.

$$= (1/7) \sum_{j=1}^7 x_{12,j}$$
- s_L = standard deviation (of daily averages of logarithms) computed from the 12 \bar{x}_i 's for the 12 days sampled during the reference period.

$$= [(1/11) \sum_{i=1}^{12} (\bar{x}_i - \bar{x}_\bullet)^2]^{(1/2)}$$
- α_\bullet = long-term average work shift concentration during the reference period from which 12 sampling days were randomly selected.
- $\hat{\alpha}_\bullet$ = estimate of α_\bullet (based on seven grab samples per sampling day) during the reference period from which 12 sampling days were randomly selected.

$$= \exp [\bar{x}_\bullet + 0.5 s_L^2]$$
- LCL = 95% one-sided lower confidence limit for α_\bullet .

$$= \hat{\alpha}_\bullet / [1 + 1.796 s_L (0.1 + 0.05 s_L^2)^{(1/2)}]$$
- UCL = 95% one-sided upper confidence limit for α_\bullet .

$$= \hat{\alpha}_\bullet / [1 - 1.796 s_L (0.1 + 0.05 s_L^2)^{(1/2)}]$$
- α_i = average work shift concentration for day i , where $i = 1, 2, \dots, 12$ and day i is the i th day in a time-ordered sequence of the 12 days that were randomly selected from the reference period.
- $\hat{\alpha}_i$ = estimate of α_i (based on seven grab samples), where $i = 1, 2, \dots, 12$ and day i is the i th day in a time-ordered sequence of the 12 days that were randomly selected from the reference period.

$$= \exp [\bar{x}_i + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_i]$$
- $\hat{\alpha}_{i+1}$ = estimated average work shift concentration for day $i+1$ (based on seven grab samples), where $i = 1, 2, \dots, 11$ and day $i+1$ is the next sampling day following day i in a time-ordered sequence of the 12 days that were randomly selected from the reference period.

$$= \exp [\bar{x}_{i+1} + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_{i+1}]$$
- $\hat{\alpha}_A$ = estimated average work shift concentration for day A (based on seven grab samples), where "day A" is a term used to designate one of the 12 randomly selected days sampled during the reference period for which the α_i value is in a critical range.

$$= \exp [\bar{x}_A + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_A]$$

- $\hat{\alpha}_B$ = estimated average work shift concentration for day B (based on seven grab samples), where day B is the first workday following day A. [Note: Day B may or may not be the next calendar day after day A since a weekend, holiday, or other non-workday may occur between days A and B.]
 = $\exp [\bar{x}_B + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_B]$
- $\hat{\alpha}_{11}$ = estimated average work shift concentration (based on seven grab samples) on the 11th of the 12 randomly selected days sampled during a reference period.
 = $\exp [\bar{x}_{11} + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_{11}]$
- $\hat{\alpha}_{12}$ = estimated average work shift concentration (based on seven grab samples) on the last of the 12 randomly selected days sampled during a reference period.
 = $\exp [\bar{x}_{12} + 0.5 (1 - 1/7) \ln^2(1.3335)] = 1.036 \exp [\bar{x}_{12}]$

H. Rationale for the Critical Points in the Sampling Strategy

NIOSH recognizes that the concentration of radon progeny in any work area varies with time. Therefore, exposure estimates based on one or even several grab samples may not provide an accurate measurement of the average work shift concentration. Nevertheless, NIOSH believes that by using estimates of radon progeny concentrations determined from grab sampling measurements, it is possible to determine (with at least 95% confidence) that the long-term average work shift concentration would not exceed 1/12 WL by more than a factor of 3.15, based on exposure data derived from seven grab samples taken during a single work shift ($\hat{\alpha}_i$). This factor can be reduced to 1.43 if an estimate of exposure were used based on 12 sampling days ($\hat{\alpha}_*$).

The estimates $\hat{\alpha}_i$, $\hat{\alpha}_A$, and $\hat{\alpha}_B$ for a single work shift's average concentration of radon progeny are based on an assumed log-normal distribution of intraday concentration variations with a geometric standard deviation (GSD) of 1.3335. An assumed log-normal interday distribution with a GSD of 1.3926 was used to calculate critical values of estimates to test hypotheses about the long-term average work shift concentration. The stated GSDs were computed from published historic data on intraday and interday variability of radon progeny concentrations in uranium mines [Johnson 1978]. Other data sets were examined; however, they were not suitable for estimating intraday and interday exposure variabilities that were unaffected by location. The interday and intraday variations in concentrations were modeled as independent log-normal distributions, based on general models for determining occupational exposure concentrations reported elsewhere [Bar-Shalom et al. 1975; Leidel et al. 1975, 1977].

1. Initial Compliance with the REL

Based on analysis of the Johnson [1978] data set, 0.14 WL was calculated to be the 95th percentile of a log-normal model for the distribution of the estimated daily average work shift concentrations ($\hat{\alpha}_i$'s) when the long-term average work shift concentration (α_*) was 1/12 WL. Thus when the estimated average work shift concentrations are greater

than 0.14 WL on two consecutive workdays, substantial evidence exists that the long-term average work shift concentration exceeds 1/12 WL. Therefore, when $\hat{\alpha}_A$ and $\hat{\alpha}_B$ both exceed 0.14 WL in a work area, NIOSH recommends that radon progeny concentrations be reduced in that work area by implementing work practices and engineering controls, and that the use of respiratory protection be required for all miners entering that work area. These recommendations are also made when the 95% lower confidence limit for the long-term average work shift concentration (LCL) exceeds 1/12 WL (see section D,4).

2. Return to Compliance with the REL

The NIOSH sampling strategy uses criteria with approximately 90% confidence for an initial determination that a work area is tentatively back to compliance with the REL. Specifically, estimated average work shift concentrations from two consecutive workdays (i.e., $\hat{\alpha}_A$ and $\hat{\alpha}_B$) in which both are ≤ 0.10 WL was chosen as a criterion that demonstrates reasonable evidence that the average radon progeny concentration is being controlled to ≤ 0.125 WL (i.e., 1.5 times the REL). Given the levels of intraday and interday variabilities observed in the Johnson [1978] data set, a work area with an average work shift concentration of 0.125 WL (i.e., 50% above the REL of 1/12 WL) has 0.90 probability to have one or both of a pair of consecutive estimated average work shift concentrations above 0.10 WL.

This "2-day" decision rule limits the magnitude with which a work area's average work shift concentration may exceed 1/12 WL and be undetected. This rule also has the advantage of permitting an early return to normal operations after a period of corrective actions to reduce exposure concentrations, at the expense of having less than high confidence that the REL is not being exceeded by more than 50%. However, only a small proportion of time passes until the next sampling day (as specified in the sampling strategy relative to the year), so that the 2-day rule limits the contribution of a temporarily excessive exposure in a work area to a miner's cumulative annual exposure. At a later time, the lower confidence limit criterion for noncompliance determined after 12 randomly selected sampling days (i.e., $LCL > 1/12$ WL) would be likely to detect a statistically significant increase above the REL if the long-term average work shift concentration were as high as 0.125 WL.

3. Less Frequent Exposure Monitoring

The upper confidence limit criterion (i.e., $UCL \leq 1/12$ WL) gives 95% confidence that the long-term average work shift concentration is not above 1/12 WL, under the assumption that $\hat{\alpha}_i$'s exhibit log-normally distributed random variations. The additional requirement that $\hat{\alpha}_i$ and $\hat{\alpha}_{i+1}$ do not exceed 0.14 WL is meant to detect a temporarily or periodically high average work shift concentration (i.e., high $\hat{\alpha}_i$'s that are not sustained for the full block of time from which 12 sampling days were selected). When both of these requirements are met, only 2 randomly selected sampling days are then required per 26-week block of time.

4. Cessation of Exposure Monitoring

$\text{UCL} \leq 0.063 \text{ WL}$ gives greater than 95% confidence that the long-term average work shift concentration (α_0) is $\leq 0.063 \text{ WL}$ (i.e., α_0 is no larger than 75% of the REL), under the assumption that $\hat{\alpha}_i$'s exhibit log-normally distributed random variations. Under the additional assumption that geometric standard deviations (GSDs) for intraday and interday (log-normal) variability are similar to those reported in Johnson [1978], the criterion that $\hat{\alpha}_{12}$ (the estimated average work shift concentration on the last of the 12 sampling days) be $\leq 0.033 \text{ WL}$ gives 95% confidence that a projected future reference period would have a long-term average work shift concentration $\leq 0.063 \text{ WL}$.

REFERENCES

- Bar-Shalom Y, Budenaers D, Schainker R, Segall A (1975). Handbook of statistical tests for evaluating employee exposure to air contaminants. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, Division of Laboratories and Criteria Development. DHEW (NIOSH) Publication No. 75-147.
- Johnson JR (1978). Uncertainties in estimating working level months. Chalk River, Ontario: Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, AECL-6402.
- Leidel NA, Busch KA, Crouse WE (1975). Exposure measurement action level and occupational environmental variability. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, Division of Laboratories and Criteria Development. DHEW (NIOSH) Publication No. 76-131.
- Leidel NA, Busch KA, Lynch JR (1977). Occupational exposure sampling strategy manual. Cincinnati, OH: U.S. Department of Health and Human Services, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health. DHEW (NIOSH) Publication No. 77-173.

APPENDIX V

MEDICAL ASPECTS OF WEARING RESPIRATORS*

In recommending medical evaluation criteria for respirator use, one should apply rigorous decision-making principles [Halperin et al. 1986]; tests used should be chosen for operating characteristics such as sensitivity, specificity, and predictive value. Unfortunately, many knowledge gaps exist in this area. The problem is complicated by the large variety of respirators, their conditions of use, and individual differences in the physiologic and psychologic responses to them. For these reasons, the following guidelines are to be considered as informed suggestions rather than established NIOSH policy recommendations. They are intended primarily to assist the physician in developing medical evaluation criteria for respirator use.

A. Background Information

Brief descriptions of the health effects associated with wearing respirators are summarized below. More detailed analyses of the data are available in recent reviews by James [1977] and Raven et al. [1979].

1. Pulmonary Effects

In general, the added inspiratory and expiratory resistances and dead space of most respirators cause an increase in tidal volume and a decrease in respiratory rate and ventilation (including a small decrease in alveolar ventilation). These respirator effects have usually been small both among healthy individuals and, in limited studies, among individuals with impaired lung function [Gee et al. 1968; Altose et al. 1977; Raven et al. 1981; Hodous et al. 1983; Hodous et al. 1986]. This generalization is applicable to most respirators when resistances (particularly expiratory resistance) are low [Bentley et al. 1973; Love et al. 1977]. While most studies report minimal physiologic effects during submaximal exercise, the resistances commonly lead to reduced endurance and reduced maximal exercise performance [Craig et al. 1970; Raven et al. 1977; Stemler and Craig 1977; Myhre et al. 1979; Deno et al. 1981]. The dead space of a respirator (reflecting the amount of expired air that must be rebreathed before fresh air is obtained) tends to cause increased ventilation. At least one study has shown substantially increased ventilation with a full-face respirator, a type that can have a large effective dead space [James et al. 1984]. However, the net effect of a respirator's added resistances and dead space is usually a small decrease in ventilation [Craig et al. 1970; Hermansen et al. 1972; Raven et al. 1977; Stemler and Craig 1977; Deno et al. 1981; Hodous et al. 1983].

The potential for adverse effects, particularly decreased cardiac output, from the positive pressure feature of some respirators has been

*Adapted from NIOSH Respiratory Decision Logic [NIOSH 1987].

reported [Meyer et al. 1975]. However, several recent studies suggest that this is not a practical concern, at least not in healthy individuals [Bjurstedt et al. 1979; Arborelius et al. 1983; Dahlback and Balldin 1984].

Theoretically, the increased fluctuations in thoracic pressure caused by breathing with a respirator might constitute an increased risk to subjects with a history of spontaneous pneumothorax. Few data are available in this area. While an individual is using a negative-pressure respirator with relatively high resistance during very heavy exercise, the usual maximal-peak negative oral pressure during inhalation is about 15-17 cm of water [Dahlback and Balldin 1984]. Similarly, the usual maximal-peak positive oral pressure during exhalation is about 15-17 cm of water, which might occur with a respirator in a positive-pressure mode, again during very heavy exercise [Dahlback and Balldin 1984]. By comparison, maximal positive pressures such as those during a vigorous cough can generate 200 cm of water pressure [Black and Hyatt 1969]. The normal maximal negative pleural pressure at full inspiration is -40 cm of water [Bates et al. 1971], and normal subjects can generate -80 to -160 cm of negative water pressure [Black and Hyatt 1969]. Thus while vigorous exercise with a respirator does alter pleural pressures, the risk of barotrauma would seem to be substantially less than that of coughing.

In some asthmatics, an asthmatic attack may be exacerbated or induced by a variety of factors including exercise, cold air, and stress, all of which may be associated with wearing a respirator. While most asthmatics who are able to control their condition should not have problems with respirators, a physician's judgment and a field trial may be needed in selected cases.

2. Cardiac Effects

The added work of breathing from respirators is small and could not be detected in several studies [Gee et al. 1968; Hodous et al. 1983]. A typical respirator might double the work of breathing (from 3% to 6% of the total oxygen consumption), but this is probably not of clinical significance [Gee et al. 1968]. In concordance with this view, several other studies indicated that at the same workloads heart rate does not change with the wearing of a respirator [Raven et al. 1982; Harber et al. 1982; Hodous et al. 1983; Arborelius et al. 1983; Petsonk et al. 1983].

In contrast, the added cardiac stress due to the weight of a heavy respirator may be considerable. A self-contained breathing apparatus (SCBA) may weigh up to 35 pounds. Heavier respirators can reduce maximum external workloads by 20% and similarly increase heart rate at a given submaximal workload [Raven et al. 1977]. In addition, it should be noted that many uses of SCBA (e.g., for firefighting and hazardous waste site work) also necessitate the wearing of 10-25 pounds of protective clothing.

Raven et al. [1982] found statistically significant higher systolic and/or diastolic blood pressures during exercise for persons wearing respirators. Arborelius et al. [1983] did not find significant differences for persons wearing respirators during exercise.

3. Body Temperature Effects

Proper regulation of body temperature is primarily of concern with the closed circuit SCBA that produces oxygen via an exothermic chemical reaction. Inspired air within these respirators may reach 120°F (49°C), thus depriving the wearer of a minor cooling mechanism and causing discomfort. Obviously this can be more of a problem with heavy exercise and when ambient conditions and/or protective clothing further reduce the body's ability to lose heat. The increase in heart rate because of increasing temperature represents an additional cardiac stress.

Closed-circuit breathing units of any type have the potential for causing heat stress since warm expired gases (after exothermic carbon dioxide removal with or without oxygen addition) are rebreathed. Respirators with large dead spaces also have this potential problem, again because of partial rebreathing of warmed expired air [James et al. 1984].

4. Sensory Effects

Respirators may reduce visual fields, decrease voice clarity and loudness, and decrease hearing ability. Besides the potential for reduced productivity, these effects may result in reduced industrial safety. These factors may also contribute to a general feeling of stress [Morgan 1983a].

5. Psychologic Effects

This important topic is discussed in recent reviews by Morgan [Morgan 1983a, 1983b]. There is little doubt that virtually everyone suffers some discomfort when wearing a respirator. The large variability and the subjective nature of the psycho-physiologic aspects of wearing a respirator, however, make studies and specific recommendations difficult. Fit testing obviously serves an important additional function by providing a trial to determine if the wearer can psychologically tolerate the respirator. The great majority of workers can tolerate respirators, and experience in wearing them aids in this tolerance [Morgan 1983b]. However, some individuals are likely to remain psychologically unfit for wearing respirators.

6. Local Irritation Effects

Allergic skin reactions may occur occasionally from wearing a respirator, and skin occlusion may cause irritation or exacerbation of preexisting conditions such as pseudofolliculitis barbae. Facial discomfort from the pressure of the mask may occur, particularly when the fit is unsatisfactory.

7. Miscellaneous Health Effects

In addition to the health effects (described above) associated with wearing respirators, specific groups of respirator wearers may be affected by the following factors:

a. Perforated Tympanic Membrane

While inhalation of toxic materials through a perforated tympanic membrane (ear drum) is possible, recent evidence indicates that the airflow would be minimal and rarely if ever of clinical importance [Cantekin et al. 1979; Ronk and White 1985]. In highly toxic or unknown atmospheres, use of positive pressure respirators should ensure adequate protection [Ronk and White 1985].

b. Contact Lenses

Contact lenses are generally not recommended for use with respirators, although little documented evidence exists to support this viewpoint [daRoza and Weaver 1985]. Several possible reasons for this recommendation are noted below:

(1) Corneal Irritation or Abrasion

Corneal irritation or abrasion might occur with the exposure. This would, of course, be a problem primarily with quarter- and half-face masks, especially with particulate exposures. However, exposures could occur with full-face respirators because of leaks or inadvisable removal of the respirator for any reason. While corneal irritation or abrasion might also occur without contact lenses, their presence is known to substantially increase this risk.

(2) Loss or Misplacement of a Contact Lens

The loss or misplacement of a contact lens by an individual wearing a respirator might prompt the wearer to remove the respirator, thereby resulting in exposure to the hazard as well as to the potential problems noted above.

(3) Eye Irritation from Respirator Airflow

The constant airflow of some respirators, such as powered air-purifying respirators (PAPR's) or continuous flow air-line respirators, might irritate the eyes of a contact lens wearer.

B. Suggested Medical Evaluation and Criteria for Respirator Use

The following NIOSH recommendations allow latitude for the physician in determining a medical evaluation for a specific situation. More specific guidelines may become available as knowledge increases regarding human stresses from the complex interactions of worker health status, respirator usage, and job tasks. While some of the following recommendations should be

part of any medical evaluation of workers who wear respirators, others are applicable for specific situations.

- A physician should determine fitness to wear a respirator by considering the worker's health, the type of respirator, and the conditions of respirator use.

The recommendation above leaves the final decision of an individual's fitness to wear a respirator to the person who is best qualified to evaluate the multiple clinical and other variables. Much of the clinical and other data could be gathered by other personnel. It should be emphasized that the clinical examination alone is only one part of the fitness determination. Collaboration with foremen, industrial hygienists, and others may often be needed to better assess the work conditions and other factors that affect an individual's fitness to wear a respirator.

- A medical history and at least a limited physical examination are recommended.

The medical history and physical examination should emphasize the evaluation of the cardiopulmonary system and should elicit any history of respirator use. The history is an important tool in medical diagnosis and can be used to detect most problems that might require further evaluation. Objectives of the physical examination should be to confirm the clinical impression based on the history and to detect important medical conditions (such as hypertension) that may be essentially asymptomatic.

- While chest X-ray and/or spirometry may be medically indicated in some fitness determinations, these should not be routinely performed.

In most cases, the hazardous situations requiring the wearing of respirators will also mandate periodic chest X-rays and/or spirometry for exposed workers. When such information is available, it should be used in the determination of fitness to wear respirators.

Data from routine chest X-rays and spirometry are not recommended solely for determining if a respirator should be worn. In most cases, with an essentially normal clinical examination (history and physical) these data are unlikely to influence the respirator fitness determination; additionally, the X-ray would be an unnecessary source of radiation exposure to the worker. Chest X-rays in general do not accurately reflect a person's cardiopulmonary physiologic status, and limited studies suggest that mild to moderate impairment detected by spirometry would not preclude the wearing of respirators in most cases. Thus it is recommended that chest X-rays and/or spirometry be done only when clinically indicated.

- The recommended periodicity of medical fitness determinations varies according to several factors but could be as infrequent as every 5 years.

Federal or other applicable regulations shall be followed regarding the frequency of respirator fitness determinations. The guidelines for most work conditions for which respirators are required are shown in Table V-1.

These guidelines are similar to those recommended by ANSI, which recommends annual determinations after age 45 [ANSI 1984]. The more frequent examinations with advancing age relate to the increased prevalence of most diseases in older people. More frequent examinations are recommended for individuals performing strenuous work involving the use of a SCBA. These guidelines are based on clinical judgment and, like the other recommendations in this section, should be adjusted as clinically indicated.

- The respirator wearer should be observed during a trial period to evaluate potential physiological problems.

In addition to considering the physical effects of wearing respirators, the physician should determine if wearing a given respirator would cause extreme anxiety or claustrophobic reaction in the individual. This could be done during training while the worker is wearing the respirator and is engaged in some exercise that approximates the actual work situation.

Present OSHA regulations state that a worker should be provided the opportunity to wear the respirator "in normal air for a long familiarity period..." [29 CFR 1910.134(e)(5)].* This trial period should also be used to evaluate the ability and tolerance of the worker to wear the respirator [Harber 1984]. This trial period need not be associated with respirator fit testing and should not compromise the effectiveness of the vital fit testing procedure.

Table V-1.--Suggested frequency of medical fitness determinations*

| Type of working conditions | Worker age (years) | | |
|--|--------------------|-----------------|-----------|
| | <35 | 35 - 45 | >45 |
| Most work conditions requiring respirators | Every 5 years | Every 2 years | 1-2 years |
| Strenuous working conditions with a SCBA† | Every 3 years | Every 18 months | Annually |

*Interim testing would be needed if changes in health status occur.

†SCBA = self-contained breathing apparatus.

*CFR = Code of Federal Regulations. See CFR in references.

- Examining physicians should realize that the main stress of heavy exercise while using a respirator is usually on the cardiovascular system and that heavy respirators (e.g., SCBA) can substantially increase this stress. Accordingly, physicians may want to consider exercise stress tests with electrocardiographic monitoring when heavy respirators are used, when cardiovascular risk factors are present, or when extremely stressful conditions are expected.

Some respirators may weigh up to 35 pounds and may increase workloads by 20 percent. Although a lower activity level could compensate for this added stress [Manning and Griggs 1983], a lower activity level might not always be possible. Physicians should also be aware of other added stresses, such as heavy protective clothing and intense ambient heat, that would increase the worker's cardiac demand. As an extreme example, firefighters who use a SCBA inside burning buildings may work at maximal exercise levels under life-threatening conditions. In such cases, the detection of occult cardiac disease, which might manifest itself during heavy stress, may be important. Some authors have either recommended stress testing [Kilbom 1980] or at least its consideration in the fitness determination [ANSI 1984]. Kilbom [1980] has recommended stress testing at 5-year intervals for firefighters below age 40 who use SCBA and at 2-year intervals for those aged 40-50. He further suggested that firemen over age 50 not be allowed to wear SCBA.

Exercise stress testing has not been recommended for medical screening for coronary artery disease in the general population [Weiner et al. 1979; Epstein 1979]. It has an estimated sensitivity and specificity of 78% and 69%, respectively, when the disease is defined by coronary angiography [Weiner et al. 1979; Nicklin and Balaban 1984]. In a recent 6-year prospective study, stress testing to determine the potential for heart attacks indicated a positive predictive value of 27% when the prevalence of disease was 3.5% [Giagnoni et al. 1983; Folli 1984]. While stress testing has limited effectiveness in medical screening, it could detect individuals who may not be able to complete the heavy exercise required in some jobs.

A definitive recommendation regarding exercise stress testing cannot be made at this time. Further research may determine whether this is a useful tool in selected circumstances.

- An important concept is that "general work limitations and restrictions identified for other work activities also shall apply for respirator use" [ANSI 1984].

In many cases, if a worker is physically able to do an assigned job while not wearing a respirator, the worker will in most situations not be at increased risk when performing the same job while wearing a respirator.

- Because of the variability in the types of respirators, work conditions, and workers' health status, many employers may wish to designate categories of fitness to wear respirators, thereby excluding some workers from strenuous work situations involving the wearing of respirators.

Depending on the various circumstances, several permissible categories of respirator usage are possible. One conceivable scheme would consist of three overall categories: full respirator use, no respirator use, and limited respirator use including "escape only" respirators. The latter category excludes heavy respirators and strenuous work conditions. Before identifying the conditions that would be used to classify workers into various categories, it is critical that the physician be aware that these conditions have not been validated and are presented only for consideration. The physician should modify the use of these conditions based on actual experience, further research, and individual worker sensitivities. He may also wish to consider the following conditions in selecting or permitting the use of respirators:

- History of spontaneous pneumothorax;
- Claustrophobia/anxiety reaction;
- Use of contact lenses (for some respirators);
- Moderate or severe pulmonary disease;
- Angina pectoris, significant arrhythmias, recent myocardial infarction;
- Symptomatic or uncontrolled hypertension; and
- Advanced age.

Wearing a respirator would probably not play a significant role in causing lung damage such as pneumothorax. However, without good evidence that wearing a respirator would not cause such lung damage, the physician would be prudent to prohibit the individual with a history of spontaneous pneumothorax from wearing a respirator.

Moderate lung disease is defined by the Intermountain Thoracic Society [Kanner and Morris 1975] as being present when the following conditions exist--a forced expiratory volume in one second (FEV_1) divided by the forced vital capacity (FVC) (i.e., FEV_1/FVC) of 0.45 to 0.60, or an FVC of 51% to 65% of the predicted FVC value. Similar arbitrary limits could be set for age and hypertension. It would seem more reasonable, however, to combine several risk factors into an overall estimate of fitness to wear respirators under certain conditions. Here the judgment and clinical experience of the physician are needed. Many impaired workers would even be able to work safely while wearing respirators if they could control their own work pace, including having sufficient time to rest.

C. Conclusion

Individual judgment is needed to determine the factors affecting an individual's fitness to wear a respirator. While many of the preceding guidelines are based on limited evidence, they should provide a useful starting point for a respirator fitness screening program. Further research

is needed to validate these and other recommendations currently in use. Of particular interest would be laboratory studies involving physiologically impaired individuals and field studies conducted under actual day-to-day work conditions.

REFERENCES

- Altose MD, McCauley WC, Kelsen SG, Cherniack NS [1977]. Effects of hypercapnia and inspiratory flow-resistive loading on respiratory activity in chronic airways obstruction. *J Clin Invest* 59:500-07.
- ANSI [1984]. American national standard for respirator protection-respirator use-physical qualifications for personnel, ANSI Z88.6-1984. New York, NY: American National Standards Institute, Inc., pp. 7-15.
- Arborelius M, Dahlback GO, Data P-G [1983]. Cardiac output and gas exchange during heavy exercise with a positive pressure respiratory protective apparatus. *Scand J Work Environ Health* 9:471-477.
- Bates DV, Macklem PT, Christie RV [1971]. Respiratory function in disease: an introduction to the integrated study of the lung. 2nd ed. Philadelphia, PA: W.B. Saunders Co., p. 43.
- Bentley RA, Griffin OG, Love RG, Muir DCF, Sweetland KF [1973]. Acceptable levels for breathing resistance of respiratory apparatus. *Arch Environ Health* 27:273-80.
- Bjurstedt H, Rosenhamer G, Lindborg B, Hesser CM [1979]. Respiratory and circulatory responses to sustained positive-pressure breathing and exercise in man. *Acta Physiol Scand* 105:204-14.
- Black LF, Hyatt RE [1969]. Maximal respiratory pressures: normal values and relationship to age and sex. *Am Rev Respir Dis* 99:696-702.
- Cantekin EI, Bluestone CD, Saez CA, Bern SA [1979]. Airflow through the eustachian tube. *Ann Otol* 88:603-612.
- CFR. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.
- Craig FN, Blevins WV, Cummings G [1970]. Exhausting work limited by external resistance and inhalation of carbon dioxide. *J Appl Physiol* 29(6):847-51.
- Dahlback GO, Balldin UI [1984]. Physiological effects of pressure demand masks during heavy exercise. *Am Ind Hyg Assoc J* 45(3):177-181.
- daRoza RA, Weaver C [1985]. Is it safe to wear contact lenses with a full-facepiece respirator? Lawrence Livermore National Laboratory manuscript UCRL-53653, pp. 1-3.
- Deno NS, Kamon E, Kiser DM [1981]. Physiological responses to resistance breathing during short and prolonged exercise. *Am Ind Hyg Assoc J* 42(8):616-23.

- Epstein SE [1979]. Limitations of electrocardiographic exercise testing [Editorial]. *N Engl J Med* 301(5):264-65.
- Folli G [1984]. Exercise EKG in asymptomatic normotensive subjects [Reply to letter to the editor]. *N Engl J Med* 310(13):852-53.
- Gee JBL, Burton G, Vassallo C, Gregg J [1968]. Effects of external airway obstruction on work capacity and pulmonary gas exchange. *Am Rev Respir Dis* 98:1003-12.
- Giagnoni E, Secchi MB, Wu SC, Morabito A, Oltrona L, et al. [1983]. Prognostic value of exercise EKG testing in asymptomatic normotensive subjects. *N Engl J Med* 309(18):1085-89.
- Halperin WE, Ratcliffe JM, Frazier TM, Becker SP, Schulte PA [1986]. Medical screening in the workplace: proposed principles. *J Occup Med* 28(8):547-52.
- Harber P, Tamimie RJ, Bhattacharya A, Barber M [1982]. Physiologic effects of respirator dead space and resistance loading. *J Occup Med* 24(9):681-84.
- Harber P [1984]. Medical evaluation for respirator use. *J Occup Med* 26(7):496-502.
- Hermansen L, Vokac Z, Lereim P [1972]. Respiratory and circulatory response to added air flow resistance during exercise. *Ergonomics* 15(1):15-24.
- Hodous TK, Petsonk L, Boyles C, Hankinson J, Amandus H [1983]. Effects of added resistance to breathing during exercise in obstructive lung disease. *Am Rev Respir Dis* 128:943-48.
- Hodous TK, Boyles C, Hankinson J [1986]. Effects of industrial respirator wear during exercise in subjects with restrictive lung disease. *Am Ind Hyg Assoc J* 47:176-80.
- James RH [1977]. Breathing resistance and dead space in respiratory protective devices. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 77-161.
- James R, Dukes-Dobos F, Smith R [1984]. Effects of respirators under heat/work conditions. *Am Ind Hyg Assoc J* 45(6):399-404.
- Kanner RE, Morris AH, ed. [1975]. Clinical pulmonary function testing: a manual of uniform laboratory procedures for the intermountain area. 1st ed. Salt Lake City, UT: Intermountain Thoracic Society.
- Kilbom A [1980]. Physical work capacity of firemen. *Scand J Work Environ Health* 6:48-57.

Love RG, Muir DCF, Sweetland KF, Bentley RA, Griffin OG [1977]. Acceptable levels for the breathing resistance of respiratory apparatus: results for men over the age of 45. *Br J Ind Med* 34:126-29.

Manning JE, Griggs TR [1983]. Heart rates in fire fighters using light and heavy breathing equipment: similar near-maximal exertion in response to multiple work load conditions. *J Occup Med* 25(3):215-18.

Meyer E, Gurtner HP, Scherrer M [1975]. Physiological appraisal of a new respirator with positive pressure. *Pneumology* 153:61-72.

Morgan WP [1983a]. Psychological problems associated with the wearing of industrial respirators: a review. *Am Ind Hyg Assoc J* 44(9):671-76.

Morgan WP [1983b]. Psychological problems associated with the wear of industrial respirators. *J Int Soc Respir Prot* 1:67-108.

Myhre LG, Holden RD, Baumgardner FW, Tucker D [1979]. Physiological limits of firefighters. Brooks AFB, TX: Air Force School of Aerospace Medicine, ESL-TR-79-06.

Nicklin D, Balaban DJ [1984]. Exercise EKG in asymptomatic normotensive subjects [Letter to the editor]. *N Engl J Med* 310(13):852.

Petsonk EL, Hancock J, Boyles C [1983]. Physiologic effects of a self-contained self-rescuer. *Am Ind Hyg Assoc J* 44(5):368-73.

Raven PB, Davis TO, Shafer CL, Linnebur AC [1977]. Maximal stress test performance while wearing a self-contained breathing apparatus. *J Occup Med* 19(12):802-06.

Raven PB, Dodson AT, Davis TO [1979]. The physiological consequences of wearing industrial respirators: a review. *Am Ind Hyg Assoc J* 40(6):517-34.

Raven PB, Jackson AW, Page K, et al. [1981]. The physiological responses of mild pulmonary impaired subjects while using a "demand" respirator during rest and work. *Am Ind Hyg Assoc J* 42(4):247-57.

Raven PB, Bradley O, Rohm-Young D, McClure FL, Skaggs B [1982]. Physiological response to "pressure-demand" respirator wear. *Am Ind Hyg Assoc J* 43(10):773-81.

Ronk R, White MK [1985]. Hydrogen sulfide and the probabilities of "inhalation" through a tympanic membrane defect. *J Occup Med* 27(5):337-40.

Stemler FW, Craig FN [1977]. Effects of respiratory equipment on endurance in hard work. *J Appl Physiol* 42:28-32.

Weiner DA, Ryan TJ, McCabe CH, et al. [1979]. Exercise stress testing: correlations among history of angina, ST-segment response and prevalence of coronary-artery disease in the coronary artery surgery study (CASS). *N Engl J Med* 301(5):230-35.

DEPARTMENT OF HEALTH AND HUMAN SERVICES
PUBLIC HEALTH SERVICE
CENTERS FOR DISEASE CONTROL
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
ROBERT A. TAFT LABORATORIES
4676 COLUMBIA PARKWAY, CINCINNATI, OHIO 45226

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE. \$300

Special Fourth Class-Book



POSTAGE AND FEES PAID
U.S. DEPARTMENT OF HHS
HHS 396