# 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

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# CONTENTS

# 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 X $10^5$ 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 $101 \pm 8$ 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/m$^3$ 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. <u>Secondary Epidemiologic Studies</u>

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 the age distribution of underground miners was unrecorded, and therefore, proportional mortality was used instead of the lifetable 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 $6.6X10^{-6}$ /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 $0.31X10^{-2}$ and $B_2$, the excess relative risk per unit of cigarette smoke exposure, was $0.51X10^3$).

### 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<br>(median=430) | 62,556 | 185.0 | 38.4 | 482 |
| Czechoslovakian[b] Uranium Miners | Placek et al. (1983) [22]<br>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 "premalignant" 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]: |
|---|---|
| 1. The test should be "effective" in terms of its validity, reliability, sensitivity, specificity, and operational characteristics (such as predictive value). | 1. The test should be "effective" in terms of its validity, reliability, sensitivity, specificity, and operational characteristics (such as predictive value). |
| 2. The test should be "acceptable" to workers in terms of its cost, convenience, accessibility, lack of morbidity. | 2. The test need not be uncomplicated or inexpensive, but its performance and interpretation must be done by competent professionals. |
| | 3. The test must be "acceptable" to workers in terms of its cost, convenience, accessibility, lack of morbidity. |
| | 4. The test results must be evaluated by comparison to a suitable population, not necessarily the general population. |
| | 5. Action levels and related medical decisions must be determined in advance of screening (based on #1 above). |

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

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 1990.103 [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.

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# 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 open-pit | underground | Production (thousand short tons) | Concentration of alpha radiation (WL) | Output by mining method (%) |
|---|---|---|---|---|---|
| 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) |

[a] Data 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.

[b] A small, undetermined number are open-pit mines.

[c] A small, undetermined number are underground mines.

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

| Year | Underground | | Open-pit | | Technical | Other | Supervisory | Total |
|---|---|---|---|---|---|---|---|---|
| | miners | service and support | miners | service and support | | | | |
| 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] |

[a] Includes 201 truckers and 371 employees involved in shaft sinking and construction.

[b] May 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 | --- |
| | 1980 | --- | 2.4 | 95 | 0 |
| Open-pit | 1980 | --- | 0.12 | 285 | 0 |

---

[a] The maximum permissible exposure in many countries.

[b] Data 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

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

[a] If not otherwise noted, the mines are iron, zinc, lead, copper, or gold mines.

[b] This value is called "typical" for large nationalized coal mines.

[c] Based 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 |
| Salaried | 1,015 | 0.97 | 585 | 1.10 |
| 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 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 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) | 7-year Average |
| ≤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 | - | - |

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

[b] N 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 |

[a] There 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.

[b] Exposures reported in this survey are based on more than 130,000 determinations of radon daughter concentrations.

[c] Production includes production and development miners.

[d] Maintenance includes mechanics and electricians.

[e] Service includes motormen, haulage crews, drift repairmen, station tenders, skip tenders, etc.

[f] Salaried 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 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 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 | 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 |

[a] No 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).

[b] Operators 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.

[c] Production includes production and development miners. In mines where production employees also perform maintenance, service and supervisory duties, such employees were classified as production workers.

[d] Maintenance includes mechanics and electricians.

[e] Service includes motormen, haulage crews, drift repairmen, station tenders, skip tenders, etc.

[f] Salaried 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 molybdeum, 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 |

[a] For 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) <0.1 | 0.1-0.3 | 0.3-1.0 | >1.0 | ALL | Weighted average annual exposure[a] (WLM) |
|---|---|---|---|---|---|---|---|---|
| | | | (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 | |

[a] The 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: <u>Radiation Hazards in Mining</u>, 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 | 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].<br>**Advantages**: particularly useful in limited areas, i.e. intake airways with high radon emanations, lunchrooms, shops, etc. [92].<br>**Disadvantages**: Too expensive to use throughout the mine. |
| Radon, Thoron Gases and Progeny | Bulkheads | 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].<br>**Advantages**: Cost-effective.<br>**Disadvantages**: Bulkheads can leak if cracked, poorly sealed, or when barometric pressure decreases. |

(Continued)

Table B-1 Mining radiation control methods (Continued)

| Type of radiation | Control method | Description |
|---|---|---|
| Radon, Thoron Gases and Progeny | Backfilling | 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].<br>**Advantages:** Reduces radon emanation, reduces ventilation requirements and provides ground support.<br>**Disadvantages:** Uranium mill tailings can still release some radiation underground, perhaps including gamma radiation. |
| Radon, Thoron Gases and Progeny | Air Cleaning | Radon daughters are removed by an air cleaning apparatus, typically involving a filtering system.<br>**Advantages:** Useful in limited areas where it is not feasible to install a large ventilation system [92].<br>**Disadvantages:** High operating costs, lack of a commercial equipment source and equipment reliability problems [92]. |
| All Radiation | Medical Removal Protection | 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.<br>**Advantages:** Protects individual miners against high cumulative exposures.<br>**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. |

(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 | 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.)<br>**Advantages**: The water cuts down on radioactive uranium ore dust.<br>**Disadvantages:** Difficult to set up in areas where water is scarce. The miners using the drill get wet. |
| Uranium Ore Dust, Radon and Thoron Progeny | Blasting at the End of Shifts | 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].<br>**Advantages**: Most miners have less exposure to dust and smoke particles and thus less radiation exposure.<br>**Disadvantages:** Extra production schedule planning is necessary. |
| Radon, Thoron Gases and Progeny | Minimizing Fan Shutdown | This involves the use of fan maintenance, backup electrical systems, and spare fans to minimize fan shutdowns during working hours. |
| Radon, Thoron Gases and Progeny | Ventilation - Blowing/ Positive Pressure | 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]. |

(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.<br>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].<br>**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.<br>**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 | The respirator is supplied with respirable breathing air from a central air supply. **Advantages:** As a temporary short-term protective measure, the supplied-air respirator affords a high degree of protection against all mine air contaminants. **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. |
| Uranium Ore Dusts, Radon, Thoron Gases and Progeny; maybe gamma | Robots or other mechanization | 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. |

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 $6.24 \times 10^6$ 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:

$R = 1+B, WLM+B_2$ PKS where:
R = relative risk
$B_1$ = excess relative risk per unit of radon progency 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:

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

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 x $10^{18}$ electrons.

Electron Volt: The change in potential energy of a particle having a charge equal to the electronic charge (1.60 x $10^{-19}$ 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, WLM+$B_2$ PKS where:
$R$ = relative risk
$B_1$ = excess relative risk per unit of radon progency 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 x $10^{12}$ 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:

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

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 $1.3 \times 10^5$ 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].