II. INTRODUCTION

A. Scope

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

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

B. Current Standard

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

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

1. Uranium Mines

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

Uranium mine operators must calculate, record, and report to MSHA the radon progeny exposure of each underground miner. The records must include the miner's time in each work area and the radon progeny concentration measured in each of those areas.

2. Nonuranium Mines

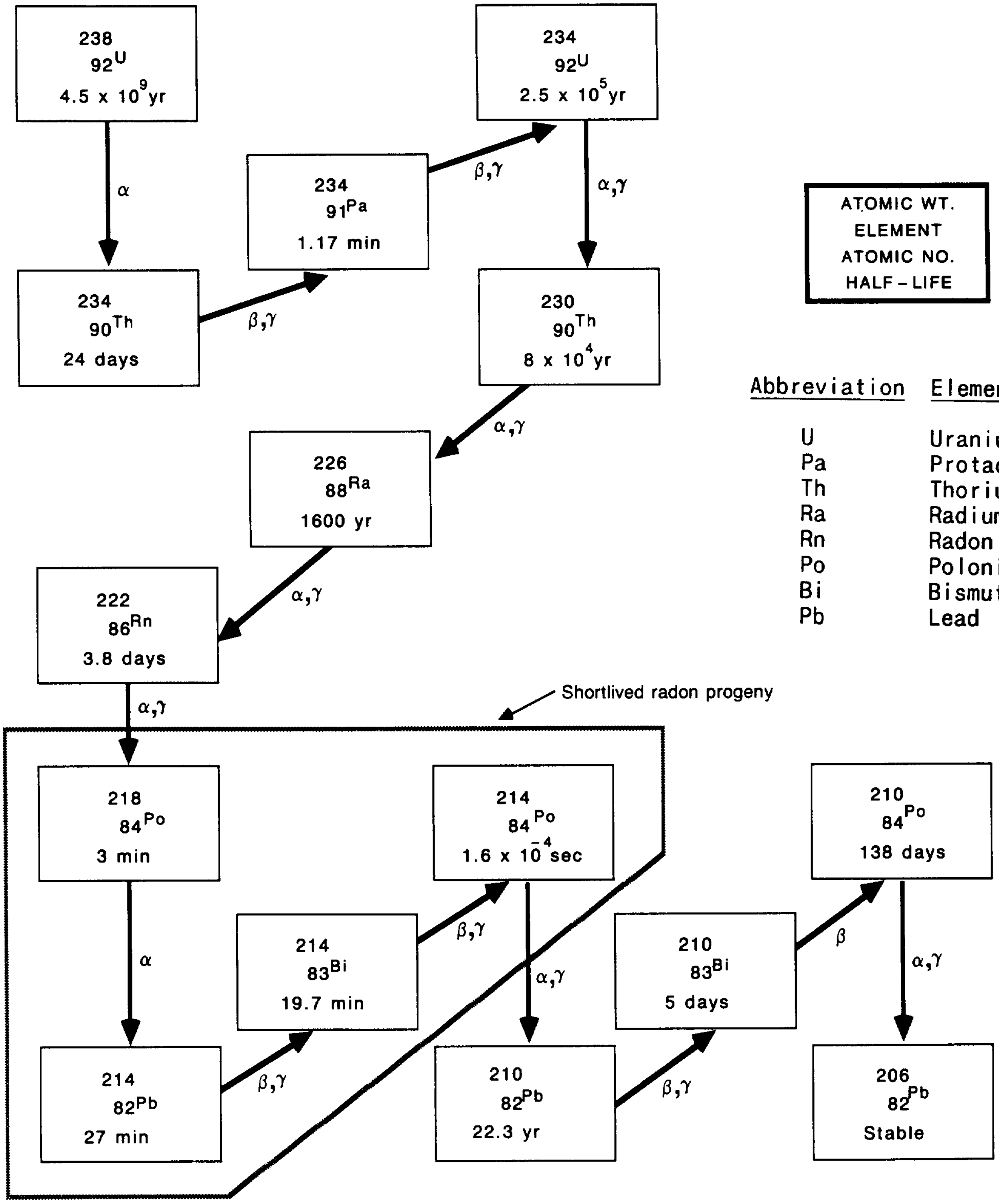
If the concentration of radon progeny in the exhaust air of nonuranium mines exceeds 0.1 WL, and if concentrations are between 0.1 and 0.3 WL in an active working area, samples representative of a worker's breathing zone must be taken at least every 3 months at random times until the concentrations of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

C. Uranium Decay Series

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

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

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



Abbreviation	Element
U	Uranium
Pa	Protactinium
Th	Thorium
Ra	Radium
Rn	Radon
Po	Polonium
Bi	Bismuth
Pb	Lead

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

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

D. Units of Measure

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

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

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

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

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

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

	Radioactivity		Potential alpha energy concentration	
Equilibrium factor (F)*	pCi	Bq	WL	J/m^3
0.30	1	0.037	0.003	6.24×10^{-8}
0.30	333	12.3	1.000	2.08×10^{-5}
0.50	1	0.037	0.005	1.04×10^{-7}
0.50	200	7.40	1.000	2.08×10^{-5}
1.00	1	0.037	0.010	2.08×10^{-7}
1.00	100	3.70	1.000	2.08×10^{-5}

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

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

E. Worker Exposure

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

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

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

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

*Adapted from Mine Safety and Health Administration data [MSHA 1986].
†Not elsewhere classified.

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

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

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

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

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

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

F. Measurement Methods for Airborne Radon Progeny

1. Description of Measurement Methods

a. Grab Sampling Methods

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

Table II-4.--Annual cumulative exposures of U.S. miners to radon progeny in 20 underground uranium mines during 1984[*],[†]

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

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

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

[§] Figures in parentheses are the % of total.

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

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

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

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

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

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[*] Adapted from Schiager et al. 1981.
[†] Used in an instant working level monitor.

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

b. Continuous Monitoring Methods

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

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

c. Personal Dosimeters

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

1. Passive Dosimeters

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

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

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

[*] Adapted from Schiager et al. 1981.

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

[§] Used in an instant working-level monitor.

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

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

*Adapted from Schiager et al. 1981.

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

2. Active Dosimeters

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

d. Factors to Consider When Selecting Measurement Methods

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

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

G. Respirator Selection and Credit for Respirator Use

1. Respirator Selection

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

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

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

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

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

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

2. Credit for Respirator Use

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

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

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

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

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

CF = the credit factor

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

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

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

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

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

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

Then rearranging terms yields

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

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

For an APF of 5, $CF = 5/[0.65 + 0.35(5)] = 2.1$
For an APF of 10, $CF = 10/[0.65 + 0.35(10)] = 2.4$
For an APF of 25, $CF = 25/[0.65 + 0.35(25)] = 2.7$
For an APF of 50, $CF = 50/[0.65 + 0.35(50)] = 2.8$
For an APF of 1000, $CF = 1000/[0.65 + 0.35(1000)] = 2.9$
For an APF of 2000, $CF = 2000/[0.65 + 0.35(2000)] = 2.9$
For an APF of 10,000, $CF = 10{,}000/[0.65 + 0.35(10{,}000)] = 2.9$

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