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EVALUATION AND CONTROL OF RADON DAUGHTER HAZARDS IN URANIUM MINES

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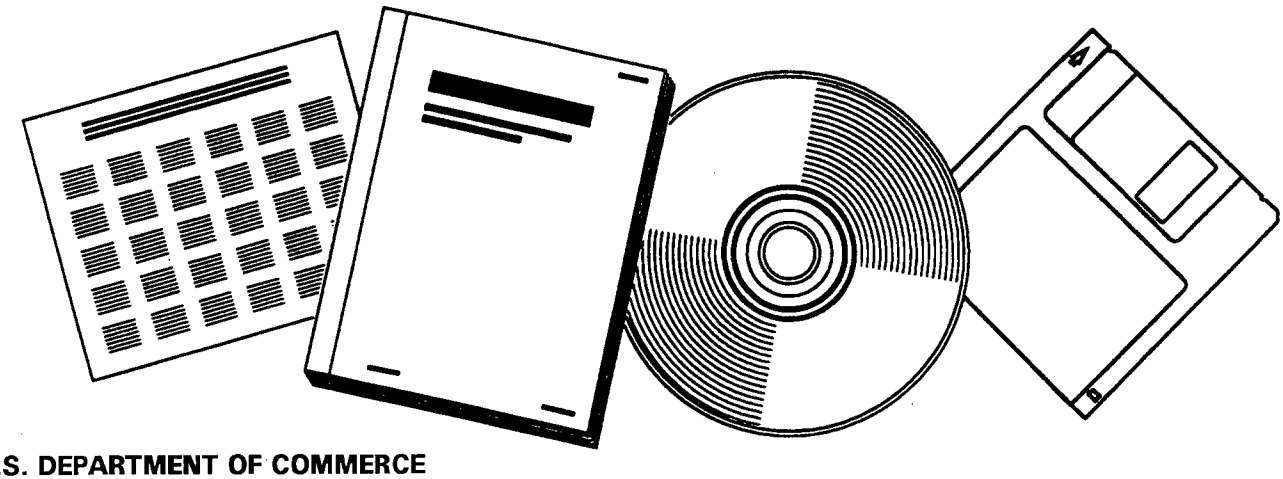

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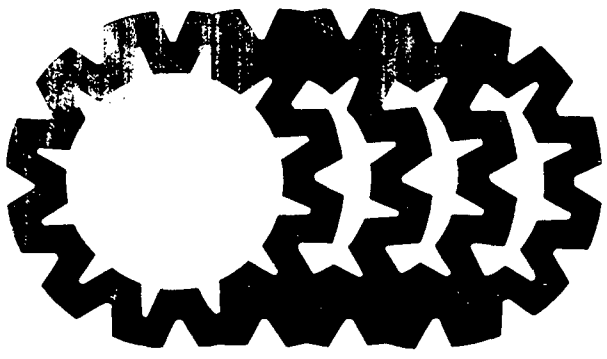

EVALUATION AND CONTROL OF RADON DAUGHTER HAZARDS IN URANIUM MINES

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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

Public Health Service

Center for Disease Control

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Health hazards which are produced by exposure to ionizing radiation are discussed. Emphasis is put on areas of evaluation of exposures to the radioactive gas Radon-222 and its short-lived transformation products, and on methods of controlling such exposures. A limited discussion of the biological effects of radon and radon daughters is undertaken, and some procedures are given for evaluating hazards created by other common contaminants of mine atmospheres. The study endeavored to assemble pertinent information and make it available to those who are concerned with producing uranium at minimal risks. Where they were available, a variety of procedures for evaluating hazards are given, and examples of systems for controlling hazards are included.

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CONTENTS

ABSTRACT

This monograph discusses primarily those health hazards which are produced by exposure to ionizing radiation. Emphasis is placed on the areas of evaluation of exposures to the radioactive gas radon 222 and its short-lived transformation products, and methods of controlling such exposures. A limited discussion of the biological effects of radon and radon daughters is undertaken, and some procedures are given for evaluating hazards created by other common contaminants of mine atmospheres. A large amount of information exists on these topics, some of which is unpublished or is not readily available. While efforts were made to obtain data from all sources, undoubtedly some valuable work was overlooked. The monograph is an endeavor to assemble pertinent information and make it available to those who are concerned with producing uranium at minimal risks. Where they were available, a variety of procedures for evaluating hazards are given, and examples of systems for controlling hazards are included.

INTRODUCTION

REQUIREMENTS FOR URANIUM

The uranium mining industry was created to supply military requirements for uranium and originally almost all of the production was purchased by governmental agencies. Since 1968 commercial sales of U_3O_8 have become increasingly important and uranium mining has now become established as an important segment of the minerals production industry. Table 1 lists commercial sales commitments which were made by United States producers as of April 1, 1968.

In addition some 3,100 tons have been sold to foreign buyers, most of which were delivered by 1970.[1] The quantity of uranium which will be produced in the future will depend on the amounts which will be required by the nuclear energy industry. Various projections have been made of the growth of nuclear power and the concomitant requirements for uranium. The most recent estimates were presented to the Uranium Committee of the American Mining Congress by Rafford L. Faulkner, Director of the United States Atomic Energy Commissions Divisions of Raw Materials on October 19, 1969, and the following information is taken from the text of this address[2]. Figures 1, 2, and 3 illustrate the estimated requirements for uranium.

Figure 1. shows the estimated annual domestic demand for uranium through 1958; the estimated production rate; and the scheduled deliveries through the same period. The estimated cumulative requirement for uranium for the period 1969 through 1980 is 212,000 tons of U_3O_8, which will increase to 450,000 tons by 1985.

Figure 2 shows that the increase in annual requirements for uranium abroad is quite similar to that in the United States. The cumulative requirements for the period 1969-1980 are estimated at 212,000 tons of U_3O_8 which will increase to about 490,000 tons by 1985.

Figure 3 shows the estimated annual Free World requirements for uranium and the scheduled commercial deliveries for the period 1969-1985. Cumulative Free World requirements by 1985 may be over 900,000 tons of U_3O_8, with an annual production rate of 125,000 tons by 1985. Substantial increases in ore production and in milling capacity will be required to meet these demands.

The uranium mining industry has thus become an important factor in meeting the energy requirements of the world. All projections indicate that, at least for an extended period, uranium must continue to be mined, and at increasing rates of production.

Table 1. QUANTITIES SCHEDULED FOR DELIVERY AS OF 1 APRIL 1968

Year of U_3O_8 Delivery	Tons of U_3O_8	Cumulative quantity Tons of U_3O_8
Pre-1968	900	900
1968	5,300	6,200
1969	4,500	10,700
1970	7,500	18,200
1971	9,800	28,000
1972	10,500	38,500
1973	7,900	46,400
1974	6,000	52,400
1975-77	6,200	58,600

From "Uranium; Production and Short Term Demand"[1]

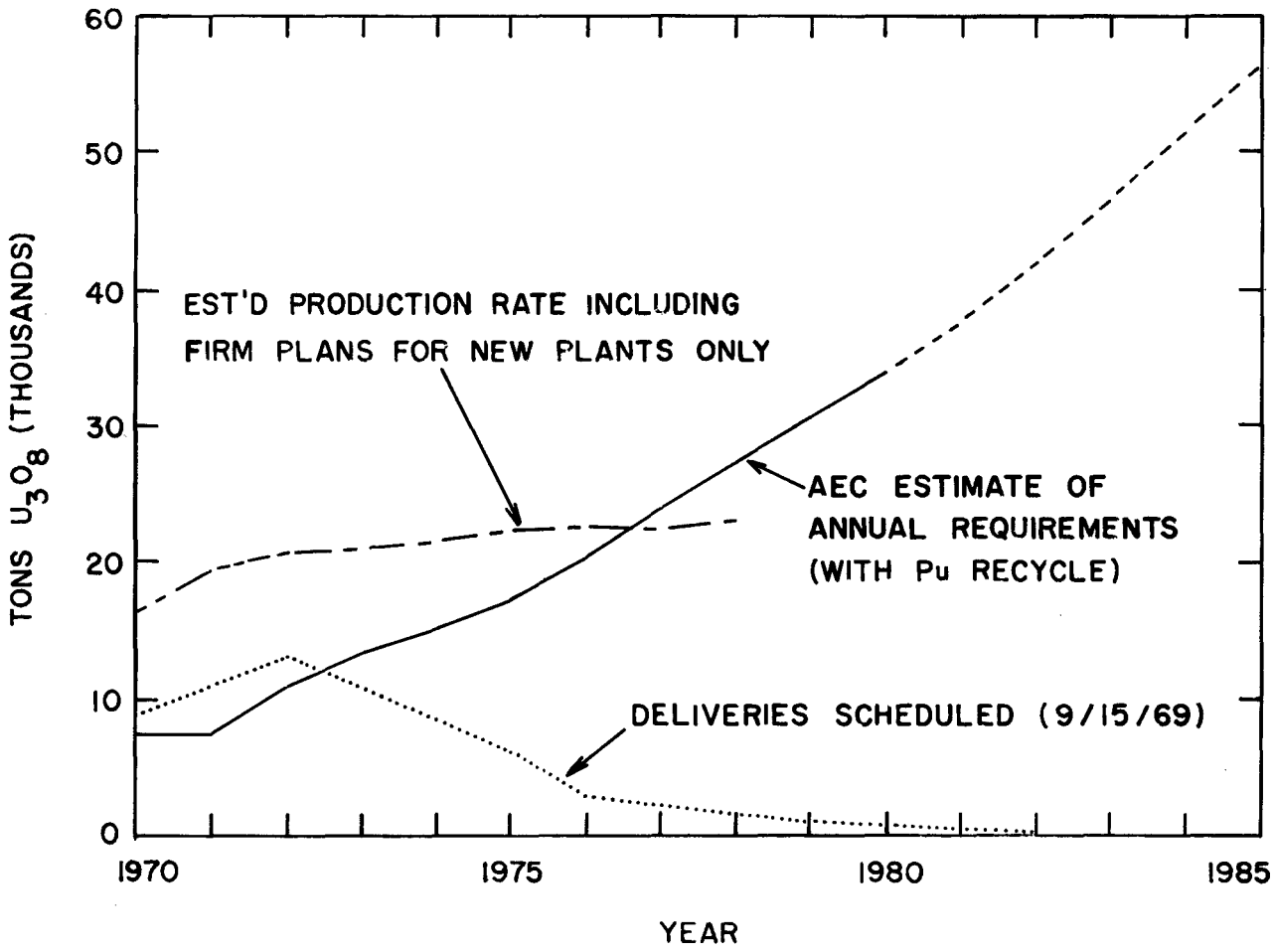

Figure 1: Estimated annual uranium requirements for domestic nuclear power plants; estimated annual uranium production capability and scheduled annual deliveries. (Faulkner[2])

HEALTH HAZARDS ASSOCIATED WITH URANIUM MINING

Uranium miners are exposed to many of the occupational disease-producing agents which exist in other metal mines. These include exposure to silicious dust, toxic metals, diesel exhaust products, oxygen-deficient atmospheres and blasting powder gases. In addition they are exposed to both external and internal radiation produced by the members of the uranium and actinium families, all of which are present in uranium ore. External radiation exposures are produced by beta particles and gamma rays emitted from ore bodies or from airborne contaminants. Internal exposures are created by inhaled radionuclides which undergo radioactive transformations in the body, emitting alpha or beta particles and gamma rays.

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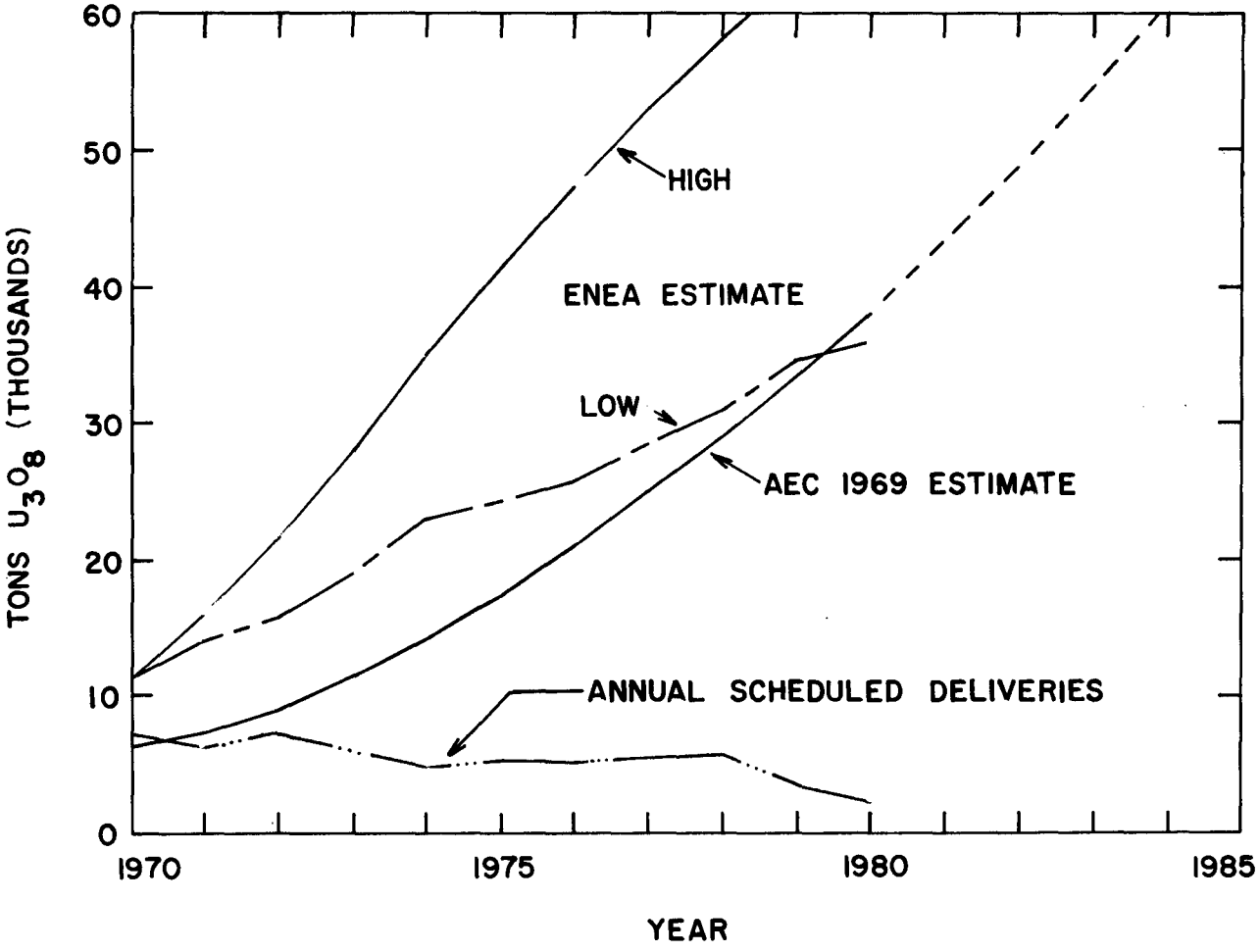

Figure 2: Atomic Energy Commission and European Nuclear Energy Agency estimates of annual foreign uranium requirements and annual scheduled commercial deliveries. (Faulkner[2])

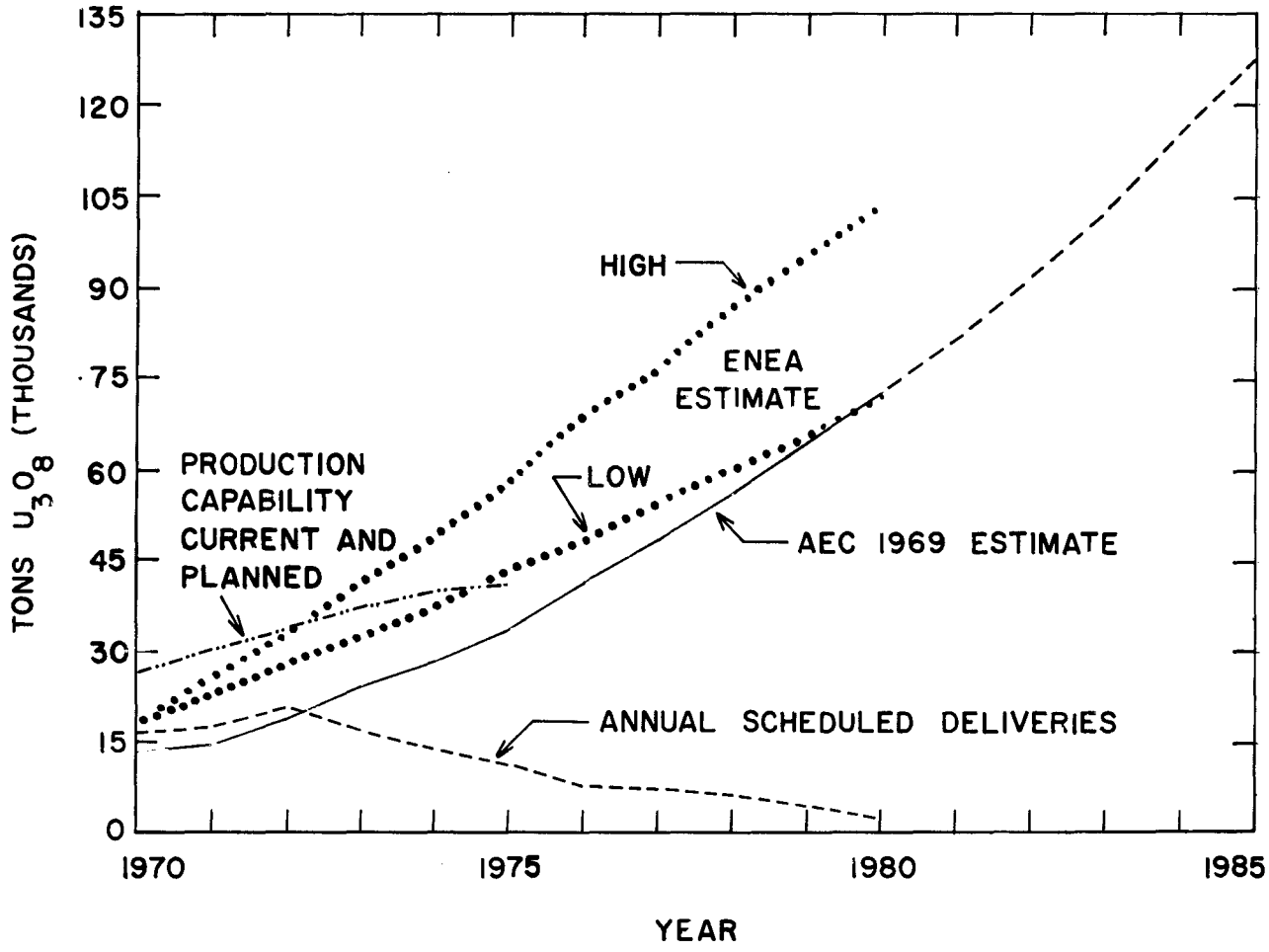

Figure 3: Atomic Energy Commission and European Nuclear Energy Agency estimates of annual Free World uranium requirements and annual scheduled deliveries. (Faulkner[2])

PHYSICAL AND CHEMICAL CHARACTERISTICS OF RADON AND DAUGHTER PRODUCTS OF RADON*

RADIOACTIVE CHARACTERISTICS OF RADON AND RADON DAUGHTERS*

Table 2 gives the characteristics of the main sequence of elements by which the most abundant isotope of uranium, ^{238}U, decays through radium and radon to a radioactively stable isotope of lead. Omitted from this table are ^{235}U, the other natural isotope of uranium and its daughter elements. The isotope, ^{235}U, comprises 0.72 percent of the mass of normal uranium. This particular isotope undergoes radioactive decay at a somewhat higher rate, so that in normal uranium for every 100 alpha particles from ^{238}U there will be 4.6 alpha particles from ^{235}U.

Moreover, ^{235}U is the parent element of a second radioactive series, the actinium series, that decays in a manner similar to ^{238}U through radium and radon isotopes to a stable isotope of lead. It differs, however, in that the radon isotope, ^{219}Rn, has a half life of but 3.92 seconds. It follows that most of this radon isotope has decayed before it is air-borne, and thus contributes very little to the hazard of the mining or processing of crude uranium.

Figure 4 shows diagramatically the radioactive decay path of ^{226}Ra derived from ^{238}U to stable lead.

SOLUBILITY OF RADON IN VARIOUS SOLVENTS

Radon is only slightly soluble in water. Significant amounts, however, are often carried dissolved in water because a large amount of radon measured in terms of radioactivity is physically small. One curie of radon weighs approximately 6.5 micrograms.

The way in which radon divides itself between water and air has been determined experimentally and the results at various temperatures have been reported in terms of partition constants (4). At a temperature of 20°C., when an equilibrium state is reached, radon will be present in water at 0.23 times the concentration that it will have in air in contact with it. Thus, water containing radon will tend to lose radon to low-radon-content air with which it comes in contact; this release occurs rapidly, particularly if the water is flowing or is otherwise agitated.

Radon is much more saluble in fats than in water. Radon solubility coefficients in a number of fatty acids and tri-glycerides were determined by Nussbaum and Hursh[5] and are listed in Table 3.

As can be seen from the table, radon solubility coefficients vary over a limited range from propionic acid through linoleic and are quite similar for the tri-glycerides tested. Because of the solubility of radon in fat, the gas will largely accumulate in the fatty tissue of humans exposed to it. Since blood contains fat, radon is more soluble in blood than in water. Under equilibrium conditions, blood in contact with air will contain 0.45 as much radon per ml of blood as is contained in a like volume of air in contact with it.

ADSORPTION OF RADON

The adsorption of radon on zinc-activated charcoal and on 4A Molecular Sieves was measured by Coleman, et al[6]. Figure 5 presents the results of these experiments.

The amount of charcoal needed to remove the radon in a given mine area can be calculated from these curves. For a small stope ($8 \times 8 \times 30$ ft.) with a radon emanation rate of about 10×10^6pCi/min, it was estimated that 825 pounds of charcoal per 24 hours would be required to maintain the radon concentration at

*The short-lived transformation products of radon, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po are commonly referred to as "radon daughters". This terminology seems to have been first introduced in Hevesey and Paneth's "Manual of Radioactivity" (London, Oxford Press, 1938).

Table 2. THE URANIUM DISINTEGRATION SERIES

Common name or symbol	Isotope	Principal radiations	Alpha energy (MeV)		Beta maximum energy (MeV)		Gamma ray quanta per disintegration	Average gamma ray energy (MeV)	Half life[1]
Uranium 238	92^{U238}	Alpha	4.18						4.51×10^9 y
UX_1	90^{Th234}	Beta			0.205	80%			24.1 d
UX_2	91^{Pa234}	Beta			2.32	80%			1.17 m
					1.5	13%			
					0.6	7%			
Uranium 234	92^{U234}	Alpha	4.76						2.47×10^5 y
Ionium	90^{Th230}	Alpha	4.68	75%					8×10^4 y
			4.61	25%					
Radium	88^{Ra226}	Alpha	4.78	94.3%					1,602 y
			4.69	5.7%					
Radon	86^{Rn222}	Alpha	5.486						3,825 d
Radium A	84^{Po218}	Alpha	5.998						3.05 m
Radium B	82^{Pb214}	Beta Gamma			0.65		0.82	0.295	26.8 m
Radium C	83^{Bi214}	Beta			3.13	23%	1.45	1.050	19.7 m
		Gamma			1.67	77%			
Radium C′	84^{Po214}	Alpha	7.68						164×10^{-6} Sec.
Radium D or Radiolead	82^{Pb210}	Beta Gamma			0.018		1.	0.047	21 y
Radium E	83^{Bi210}	Beta			1.17				5.01 d
Radium F	84^{Po210}	Alpha	5.298						138.4 d
Radium G	82^{Pb206}								Stable

Note.—All values are taken from information compiled by Hollander, Perlman, and Seaborg (1) except those for gamma radiations of RaB and RaC which have been reported by Evans and Evans (2). Numerical values for number of quanta of gamma radiation and quanta energy for these two isotopes are still uncertain. The product of number of quanta and quantum energy, that is the total gamma-ray flux, is known with greater certainty. Omitted from this table are branched disintegrations, unimportant from the health standpoint, that occur with ^{218}PO, ^{214}Bi, ^{210}Bi.

After PHS Publication No. 494, pg. 6.

1,000 pCi/1. Similar results were obtained by Schroeder, et al[7].

CHEMISTRY OF RADON

The chemistry of radon is, for the most part, similar to that of noble gases such as xenon. However, Stein[8] has recently reported that certain radon reactions are unique. Solutions of oxidizing compounds, such as chlorine fluorides, bromine fluorides, iodine heptafluoride and Ni F_6^{-2} ion in hydrogen fluoride oxidize radon to non-volatile radon fluorides. These reactions will take place at ordinary temperatures and the solutions can be evaporated to dryness leaving the radon fluorides as a residue.

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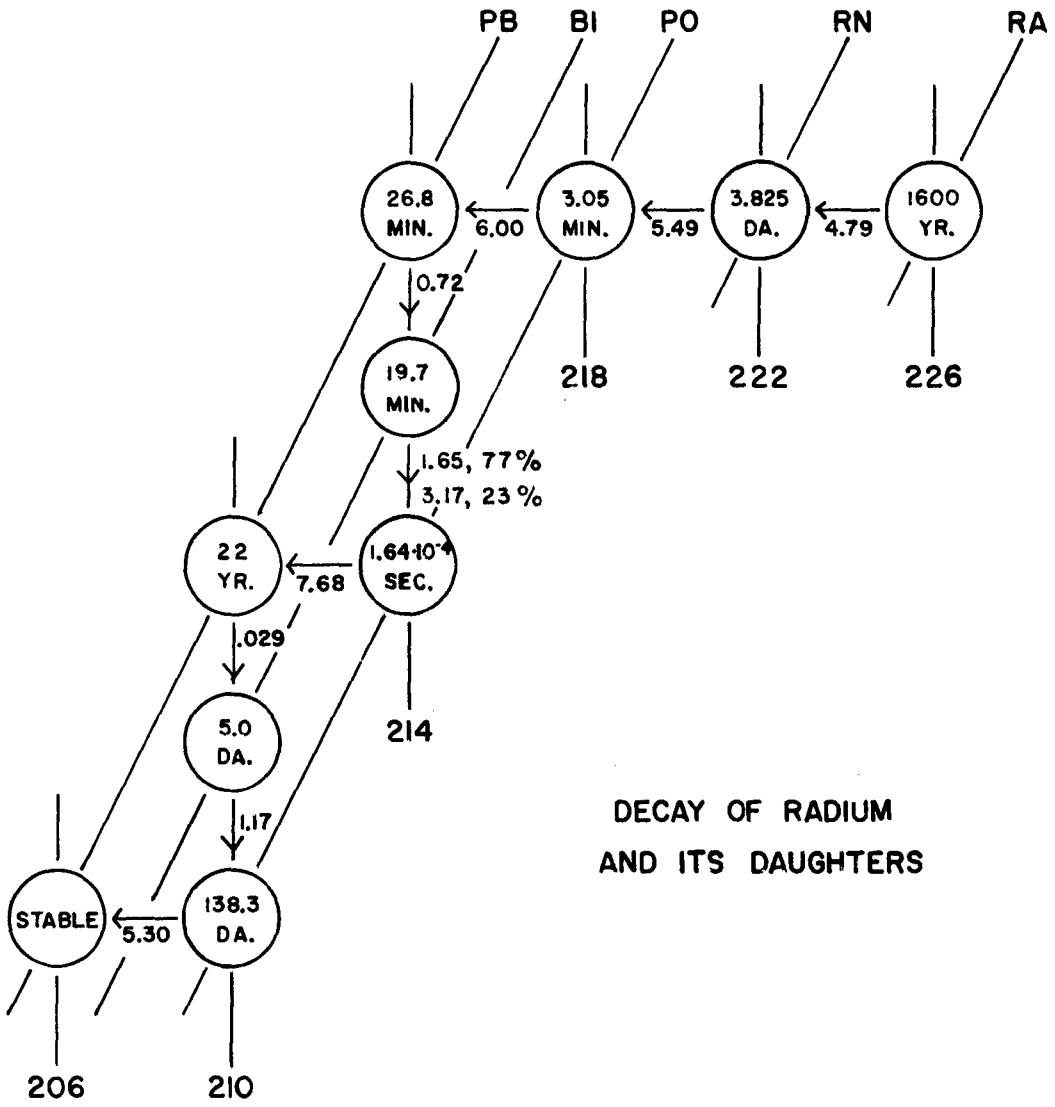

Figure 4: Radioactive decay of radium-226 to stable lead after Hursh. Alpha decay proceeds horizontally toward the left; beta decay proceeds vertically downward. Main alpha particle energies and maximum leta particle energies are noted adjacent to the arrows. Half lives are given within the circles. (PHS Publication No. 494)

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Table 3. RADON SOLUBILITY COEFFICIENT IN FATTY ACIDS AND TRIGLYCERIDES

	a[1]		
	25°	37°	50°
Formic acid	1.05	0.96	0.95
Acetic	4.43	3.53	3.30
Propionic	6.52	5.23	5.47
Butyrie	7.52	6.82	5.99
Valeric	8.64	6.82	6.06
Hexanoic	9.03	7.23	6.16
Heptanoic	8.75	7.15	6.33
Octanoic	9.03	6.89	6.16
Nonanoic	8.32	6.89	6.00
Decanoic	—	7.13	—
Undecanoic	—	6.86	—
Lauric	—	—	5.93
Tridecanoic	—	—	5.95
Acrylic	—	5.01	—
Oleic	8.10	6.72	5.86
Linoleic	7.96	6.32	—
Triacetin	3.42	2.88	—
Tributyrin	6.42	5.01	—
Trihexanoin	7.25	6.10	5.17
Trioctanoin	7.55	6.12	5.63
Olive oil (USP)	7.70	6.26	—
Olive oil (Italian)	7.71	6.24	—
Butterfat	—	5.91	—
Rat fatty acids (extracted)	—	5.85	—
Human fat (extracted)	—	6.33	—

From Nussbaum and Hursh, J. Phy. Chem.[5]

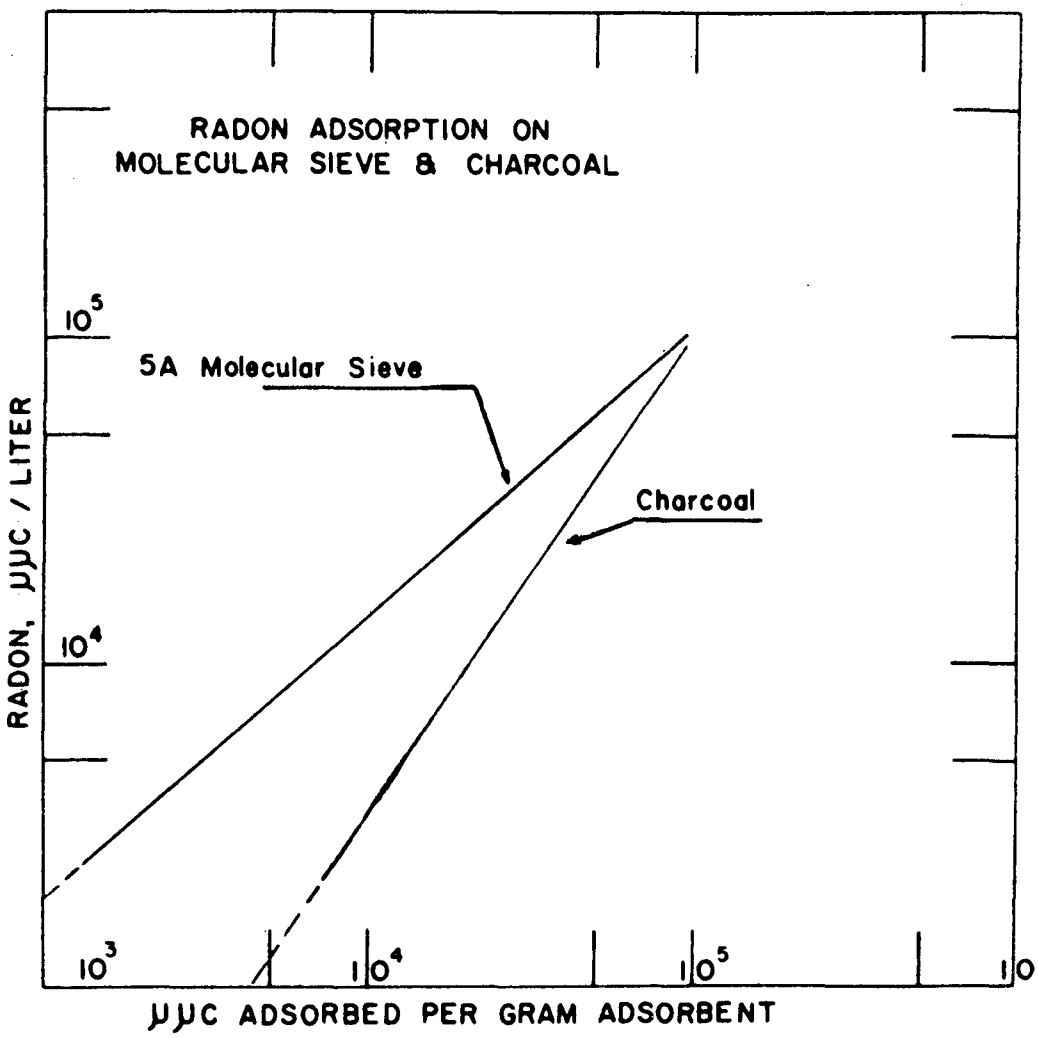

Figure 5: Adsorption of radon on molecular sieve and charcoal. Curves show the relationship between concentration of radon in air and total amount of radon adsorbed per grams adsorbent. (Coleman et al[6])

BIOLOGICAL EFFECTS OF RADON AND RADON DAUGHTERS

INTRODUCTION

This section deals with the biological effects of inhaled radon and radon daughters. Even though the primary aim of the monograph is to discuss procedures for evaluating and controlling exposures to these nuclides, awareness of the results of exposures is important to all who are responsible for conducting operations safely. No attempt will be made to treat this area in detail, as it could properly be the subject of a separate monograph. The references should be consulted for further information on specific subjects.

REVIEW OF OCCUPATIONAL EXPERIENCE

The literature abounds with reports of studies of human exposures to radon and radon daughters. With such a wealth of material available, it is necessary to choose for discussion only relatively few articles from among many excellent reports. Those given cover significant older work as well as recent publications. A detailed review of the historical record is given by Stewart and Simpson[1] and an article by Holaday[2] discusses several instances of exposure of miners to radon and radon daughters.

The classical instances occurred in the Schneeburg mines in the Erz mountains of Saxony and in mines on the Bohemian side of the Erz mountains near Jachymov (Joachimsthal). These episodes are described in W. C. Hueper's book, *Occupational Tumors and Related Diseases.*[3] The record of experience in Schneeburg is extensive and detailed with the earliest descriptions dating from the middle ages. In 1879, when Hartung and Hesse identified the disease as a malignancy of the lungs, about 650 men were employed in these mines. In the period of 1869-1877, 150 men died of lung cancer and during the next two years 75% of all deaths among miners were reported as due to this cause. From 1879-1885, 72 more deaths among active miners were reported as caused by lung cancer. As late as 1935 there appeared to be little change in the proportion of miners dying from lung cancer. Hueper estimated that there were about 400 deaths from lung cancer during the period 1869-1935. There is no information available on the total number of men who worked in the mines during this time, the number of men whose causes of death were unknown, and other pertinent data. Silico-tuberculosis was also common in the miners.[4]

It was not until 1926 that it was recognized that the disease afflicting miners at Jachymov was similar to that at Schneeburg. Therefore, early records do not exist for this episode. Autopsy studies made in 1929-1930 by Pirchan and Sikl[5, 6] showed that about 50% of the deaths among the miners were caused by lung cancer, which was very similar to the situation at Schneeburg. Pierquin et al[7] quoted Baader as reporting that 180 cases of lung cancer were diagnosed in the period 1939-1943. An article by Horacek[8] reports 55 cases of lung cancer after World War II. It is uncertain how many of these cases duplicate those reported by Baader. As was the case in Schneeburg the number of men exposed is not known with any reliability.

The atmospheric concentrations of radon in the mines at Schneeburg and Jachymov have been the subject of much speculation. Measurements were made in Schneeburg in 1924 by Ludwig and Lorenser[9] and in 1934 in Jachymov by Behounek.[10] In 1942 Evans and Goodman[11] proposed an average radon concentration of about 2.9×10^{-9} curies per liter (Ci/l). Mitchell[12] in 1945 concluded that a reasonable estimate was 1.5×10^{-8} Ci/l for the period before the hazard was recognized. In both areas the workings were extensive, only natural ventilation was utilized, and the atmospheric concentrations varied widely. By any estimates, the miners were exposed to high concentrations. The ore bodies in these mines were complex, containing possibly carcenogenic elements such as arsenic and cobalt.

Diesel engines were not employed so the complicating factor of diesel fuel combustion products was not present.

A third episode which occurred in Newfoundland was described by de Villiers and Windish[13] and is discussed in detail in a Royal Commission Report[14] which investigated the situation in 1969. From 1933, when the first mine was opened, through 1967, 142 deaths occurred in employees or ex-employees who had worked over 2,000 hours underground. Fifty-one of these deaths resulted from lung cancer. The finding that 37 of these deaths occurred in men under 55 years of age is particularly striking.

The Newfoundland episode is unique in that the mines were producing fluorspar, not uranium or other metals. In only one of 16 ore samples was the concentration of uranium as high as 0.005 percent, and only traces of such elements as arsenic and cobalt were found. The source of radon was ground water which carried the gas into the mines where it was released. Radon and radon daughter surveys made in 1959 in two mines (the others had been closed and allowed to fill with water) found radon daughter concentrations ranging from 0-12 working levels (WL) in ventilated areas, and from 0.4-193 WL in dead-end areas. de Villiers and Windish suggested that average radon daughter concentrations to which the miners were exposed were in the range of 2.5-10 WL.

As stated earlier, the occupational exposures of fluorspar miners to known or suspected carcenogenic agents was essentially limited to radon and radon daughters. Diesel engines were used on one level of one mine, but this was the only complicating factor. In spite of the lack of environmental data before 1959, continued observation on this group can yield useful information on the relationship between total radiation exposure and increase in incidence of lung cancer.

The most thoroughly investigated instance of exposure of miners to radon daughters has occurred in United States uranium mines. Many more men working in many more mines were involved in this episode than in those described earlier. The ore bodies in most of these mines were located in sandstone; relatively few were in limestone, and the others were in a variety of host materials. For the most part other potentially toxic elements occurred in trace amounts only. Table 4 summarizes data on concentrations of selected trace elements.

Table 4. CONSTITUENTS OF ORES IN U.S. URANIUM MINES*

Constituents	Percent
Free silica	30.0-40.0
Aluminum	0.1-20.0
Iron	0.1- 6.0
Calcium carbonate	0.06-10.0
Uranium	0.01- 0.5
Vanadium	0.0009- 2.8
Cobalt	0.0004- 0.1
Arsenic	0.0004- 0.05
Nickel	0.0002- 0.04
Chromium	0.0001- 0.1
Selenium	0.00003- 0.4

*After U.S. Department of Interior, Geological Survey, Washington, D. C.
All other metallic constituents individually are within the concentration range for selenium.

A study of environmental conditions in these mines was initiated in 1950 by the United States Public Health Service and the responsible agencies in the uranium mining states. An epidemiological study of a selected group of men who worked in American uranium mines was started in 1954 which is continuing. Several analyses of their mortality experience have been reported.[15, 16, 17, 18, 19]

Data from this study have been employed to construct exposure-response curves. The summary and conclusions of the most recent report, 1971, were:

"Epidemiologic evidence supported by pathologic observations have left little doubt that airborne radiation is the major causal factor in the excess of respiratory cancers among uranium miners as a group. The role of alpha radiation in the etiology of respiratory cancer risk at low cumulative levels of exposure, however, has been the subject of debate. The present report has presented data supporting a causal relation between cumulative airborne radiation exposure in the (120-359 WLM) range and an increased risk of respiratory cancer. Other evidence as it relates to the present (12 WLM) and proposed (4 WLM) annual permissible level of radon daughter exposure for uranium miners was considered.

A. A statistically significant excess of respiratory cancer was observed among white uranium miners at each cumulative radiation exposure

category down to and including 120-359 WLM.

B. An increased mortality from respiratory cancer, as well as an exposure-response relationship, was demonstrated among uranium miners with and without other hard rock mining experience.

C. A statistically significant excess of respiratory cancer deaths at 120-359 WLM and above persisted after consideration was given to cigarette smoking and to metropolitan residency.

D. The lack of a differential respiratory cancer risk between surface workers and underground miners of the potash industry was contrary to the hypothesis that an excessive respiratory cancer risk is associated with underground mining in the absence of elevated radon daughter levels, i.e., <0.02 WL.

E. A paucity of respiratory cancer deaths during the first five years after onset of uranium mining (among men with no other hard rock mining), followed by a statistically significant excess risk for each time interval beyond 10 years was not consistent with a predisposition to respiratory cancer among individuals employed in uranium mining.

F. The extremely low rate of respiratory cancer among United States Indians, resident in the Southwest, was not sufficient to permit detection of an increased respiratory cancer relative risk similar to that of white uranium miners, among nonwhite uranium miners (99% were Indian), when contrasted with all nonwhite males of the four-state area.

G. A statistically significant excess of small cell undifferentiated type tumors among uranium miners with respiratory cancer as contrasted with age-cigarette matched controls was demonstrated at each cumulative radiation exposure category down to and including 201-700 WLM. A similar excess, though not significant, was observed among uranium miners who had as little as 40-200 cumulative WLM. The relative frequency of this cell type was shown to increase with increasing cumulative radiation exposure. These findings are consistent with the mortality results in the 120-359 cumulative WLM range.

H. Extensive analyses were done to evaluate possible bias in radiation exposure attributed to Study Group miners. WLM estimates from both uranium and other hard rock mining were found to be generally reasonable. Starting with mine inspectors (who tend to sample those parts of mines having high WL values more frequently) and checking the various manipulations of mine WL levels and occupational histories, it is evident that miners are more likely to be misclassified into higher WLM categories than into lower ones. These evaluations have failed to find any plausible alternative to the hypothesis that radon daughter exposure is causally related to the excess lung cancer risk in the 120-359 WLM category. Because of the tendency toward overestimation of exposures, persons in this category probably have had even less exposure than indicated.

I. Other epidemiological studies of situations where human lungs were irradiated were not only consistent with the observations of lung cancer in uranium miners, but indicate that excess lung cancer occurs at lower radiation levels than could be adequately studied among uranium miners.

J. Experimental studies with animals confirm that the lung is relatively radiosensitive from the standpoint of carcinogenesis, and are consistent with human studies in that lung cancer may result from exposures on the order of 100 rads or less.

K. Three approaches have been used to evaluate the lowest levels of radon daughter exposure at which health risks occur:

1. Modified life table analyses on a defined cohort of uranium miners to determine mortality of respiratory cancer by cumulative WLM categories. Possible causes of observed increases other than radiation were evaluated.
2. Conversion of the radiation protection guide of 15 rems per year to its equivalent in Working Level Months.
3. Evaluation of respiratory cancer risk at low levels by use of a model which compensated for the variable induction-latent periods of men in different WLM categories.

Each of the three approaches indicates that exposures in the range of 120 to 360 WLM do increase the risk of respiratory cancer.

L. Cigarette smoking, diesel smoke, and exposure to miscellaneous dusts may have contrib-

uted to the development of lung cancer in some miners by affecting the distribution of radon daughters within the lung or by acting as promoting agents. Cigarette smoking is not only harmful to uranium miners, just as it is to other men, but it also appears to be more so in combination with radon daughter exposure. Although cigarette smoking should be discouraged among uranium miners, as among other people, and other noxious agents in mine atmospheres should be reduced to a minimum, permissible levels for radon daughters must be based on data derived from the environment in which miners continue to work and live.

M. Experimental results, the excess lung cancer among thorotrast patients, and the similarity of risk among exposure-rate subgroups of United States uranium miners, all support the NCRP statement that there is no dose-rate effect in the biological response to high linear energy transfer radiation. There is, therefore, no scientific reason to suspect that dose-rate has influenced the respiratory cancer risk among miners exposed in the 120 to 360 WLM range.

N. The risk of respiratory cancer per unit of exposure appeared to be greater in the lower cumulative radiation groups than in the higher ones. This observation may be made from the modified life table analyses as well as the computational model analyses. Thus a reduction in radon daughter exposure from 12 to 4 WLM per year may not yield the same proportionate reduction in respiratory cancer as would be expected from a linear relationship, i.e., an assumption of linearity appears not to be conservative."

These instances have produced a voluminous documentation of the results of exposure to radon and radon daughters in underground uranium mines. However, firm predictions to the effect of long-term exposure to relatively low levels of these elements are difficult to make. In all cases, exposures were to relatively high atmospheric concentrations of radon daughters, and the environmental data are not as complete as would be desired.

REVIEW OF EXPERIMENTAL OBSERVATIONS

The literature contains many reports of investigations in which small animals were exposed to radon and the physiological and pathological effects were observed. The early work was done before the significant role played by radon daughters in delivering radiation to tissue was realized and the atmospheric concentrations of these radionuclides were not measured. Therefore, the results of these experiments cannot be compared with later work.

Extended and comprehensive reports by Morken and Scott [20] and Pohl[21] supply much of the following material. The reports of Rajewsky, Schraub, Aurand, Jacobi and others at the Max Planck Institute for Biophsik at Frankfort should also be referred to for complete coverage (references to these studies are given in both reports). The primary objective in Morken's experiments was to determine physiological and pathological effects of long-continued exposure to radon and radon daughters. Mice were exposed to an atmosphere containing 0.42 microcurie of radon per liter (uCi/l), The RaA, RaB and RaC-C[1] concentrations on dust were 0.34, 0.20 and 0.10 uCl/l respectively. The radioactivity content of the atmosphere corresponded to about 1400 WL. The animals were exposed for 150 hours per week throughout their life. The notable effects were shortening of life span and arrestment of growth. The median life span during exposure was 35 weeks as compared with 90 weeks for control animals. Body weight did not change during exposure whereas control animals continued to grow. After 35 weeks of exposure, histological studies showed severe destructive, hyperplastic and metaplastic lesions in lung tissue, mainly in the trachea and bronchi. However, no carcinomas were found. Other organs showed no injury.

Distribution of inhaled radon daughters was also studied by Morken and Scott. Mice were placed in the chamber for 24 hours, removed, allowed to breathe radon-free air to clear radon from the body and then sacrificed. The organs of interest were removed and the activity counted. The experiments showed that a large portion of the radioactivity deposited in the lung was removed rapidly and transported to other parts of the body. The distribution measurements indicated that deposition of the inhaled radioactivity in the lungs was close to 100 percent and that much of the deposited material was cleared from the respiratory tract with a physiological half-time of 10 minutes. Much of the activity was in the gastrointestinal tract, but

sufficient amounts were found in the systemic system to suggest that dust-borne activity dissolved rapidly from dust particles and entered the blood. The authors point out that these results are only qualitative. From comparison with inhalation studies using other dusts Morken and Scott conclude that a rapid clearance phase with a half-time of 30 minutes operates to remove much of any dust deposited in the lungs.

Pohl[20] studied deposition of radon daughters in the respiratory tract, translocation of these elements from the lungs to the systemic system and their distribution in body tissues. The species used for these experiments were mice and guinea pigs. He also exposed men to various concentrations of radon daughters and measured the content of RaC in blood and urine. His report describes the details of the experiments and estimates of dose to the organs measured. The results are in agreement with those of Morken and Scott in that a large amount of the deposited radon daughters were cleared rapidly from the lungs. Pohl concluded the translocation of decay products was mainly due to direct resorption in the alveoli. The fraction of inhaled decay products which are deposited in this region depends on the particle size distribution of the inhaled aerosol, and availability for translocation will depend on the solubility of the aerosol and strength of attachment of daughter atoms to the particle. Therefore, results of single experiments varied widely. The data reported are means of many experiments.

Pohl considered that the pattern for decay product distribution in guinea pigs was similar to that for man and therefore the results of one series of tests with this species are presented here. The animals were exposed to an atmosphere containing 1,000 picocuries of radon per liter (pCi) for over three hours, RaA, RaB and RaC were in equilibrium with radon. The esophagus of each animal was ligated to prevent ingestion of daughter products. Measurement of RaC activity in the organs demonstrated that as expected the lungs showed the greatest concentration followed by kidney, blood and liver. The specific activities found in pCi/g were: lung, 263; kidney, 18.2; blood, 6.85; liver, 5.15.

Pohl also exposed five groups of men for periods of two hours in atmospheres containing varying concentrations or radon daughters. Blood and urine samples were analysed for RaC. The results of these tests are listed in Table 5.

These results indicate that in man, as well as other species, appreciable amounts of radon daughters are translocated from the lungs to the systemic system, and that radon absorbed from the lungs contributes very little to the RaC in the systemic system.

Failure to induce lung cancer by exposing animals to radon and radon daughters is consistent with the results of tests with chemical carcenogens. For example, Kuschner et al[22] state: "The initiation of lung cancer undoubtedly depends on the interplay of a group of controlling or modifying factors in which the carcinogen may

Table 5. SPECIFIC ACTIVITY pCi/g OF RaC IN BLOOD AND URINE FOLLOWING TWO HOURS INHALATION OF AIR CONTAINING 1000 pCi Rn per liter

Inhalation room temperature and relative humidity	Equilibrium ratios in the air. Rn: RaA: RaB: RaC:	Percent maximum possible RaC	No. of subjects	Blood RaC Mean	Blood RaC Range	Blood RaC/RaB	Urine RaC Mean	Urine RaC Range	Urine RaC/RaB
Thermalstollen, 1962 38-41°C 100%	1:1:0.85:0.8	77%	12	4.8	(3.0-8.9)	1.4	6.5	(2.1-14.0)	3.0
Thermalstollen, 1963 38-41°C 100%	1:0.8:0.6:0.5	52%	14	2.9	(1.8-6.5)	1.2	7.9	(2.8-12.5)	2.5
Emanatorium, Innsbruck. 24°C 70%	1:1:0.9:0.8	79%	20	4.4	(2.1-6.3)	1.2	6.4	(3.4-10.3)	2.5
Emanatorium, Innsbruck. 24°C 70%	1:1:0.5:0.4	45%	16	2.4	(1.8-4.0)	1.1	3.0	(1.8-7.4)	2.3
Daughter product free air	1:0.05:0.0:0.0	0.2%	10	0.24	(0.1-0.5)	1.0	0.79	(0.4-1.1)	2.0

After Pohl, Sitzungsber, Osterr, Akad, Wiss.[20]

be essential but not sufficient in itself to complete the induction process." Studies in which animals are exposed to atmospheres simulating mine conditions (dust and oil mist, for example) might be fruitful.

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DOSIMETRIC CONSIDERATIONS

INTRODUCTION

The subject of lung dosimetry as related to inhalation of radon daughters is intriguing and extremely complex. It is intriguing because individuals exposed to these radionuclides comprise the largest group of workers who have received, and are still receiving, biologically significant doses of alpha radiation from inhaled particulates. Furthermore, as radon daughters occur everywhere, the exposure of uranium miners is not unique, but is one of degree. Therefore, the possibility exists that information gained from the experience of this group could be utilized for many other situations. It is complex because of the numerous poorly-defined factors which affect deposition and retention of particles in the respiratory system and delivery of energy from alpha particles to critical tissue. The complexity of the situation has not halted work to resolve it and many models have been developed which have been used to estimate the radiation doses to which lung tissue might be subjected as a consequence of inhaling radon daughters.

Detailed reviews and evaluations of the subject of lung dosimetry relating to inhalation of radon daughters have been conducted by Parker[1, 2] and by Nelson, Parker et al[3]. These reports consider the various models which have been proposed from the early work of Evans and Goodman[4] to that reported by Holleman, Martz and Schiager[5]. Factors affecting deposition and retention of mine aerosols were considered as well as the physical and biological parameters which influence the quantity of radiation delivered to tissue in various regions of the respiratory tracts. As these comprehensive reviews are available for detailed information, this section will only summarize present knowledge on the question of lung dosimetry.

PARAMETERS AFFECTING RADIATION DOSE

Nelson and Parker[3] considered the following parameters which would affect uranium miner lung dosimetry:

1. The characteristics of the mine atmosphere
2. Lung model and breathing patterns
3. Deposition of radon daughters in the respiratory tract
4. Regional translocation and equilibrium activities
5. Target tissue and dose

The term "characteristics of the mine atmosphere" refers to such items as the ratio between the number of particles and number of daughter atoms per unit volume; the size distribution of particles to which daughter atoms are attached; and the fraction of daughters of each isotopic species which exist as unattached atoms. Studies of these parameters are not simple, and those which have been reported,[5, 6, 7, 8, 9, 10] while valuable, still do not describe conditions with the precision those estimating lung doses desire. As these characteristics affect deposition and translocation in the respiratory tract they are important factors. No extensive series of measurements have been reported of number concentrations and size distribution of particulates in uranium mine atmospheres. Both Holleman[5] and Raabe[11] suggest that in the majority of mine situations, atmospheric nuclei carried in by ventilation air will far outweigh in numbers the particles generated by mining operations. Therefore, the size distribution spectrum of particles to which radon daughters are attached may not vary widely. Areas with very low ventilation rates, or where diesel engines are used, would be exceptions to this general statement. Studies to clarify this situation are badly needed.

Nelson and Parker reviewed reports of investigations of the effect of breathing patterns on total respiratory deposition of radon daughter.[5, 12] Both studies showed that in relatively constant atmospheres, the total respiratory deposition was a function of respiration rate and tidal volume. The value measured ranged from 23 to 45 percent in George and Breslin's work and 30 to 65 percent in Holleman et al's report.

CONCLUSION

After considering the ranges of uncertainties in the assumptions which are made in estimating lung dosages resulting from inhalation of radon daughters, Nelson and Parker concluded that the state of modelling leads to an order-of-magnitude of cancer related dose, which they considered to be high enough to confirm the credibility of cancer induction at the levels of exposure which existed in uranium mines in the past. They considered the modelling inadequate to characterize a permissible level with confidence. They believed that the calculated dose was sufficiently flat over a number of Weibel generations of the model to prevent pinpointing of the expected zone of cancer induction, especially as additional environmental factors might cause maximum incidence not to occur at the maximum dose zone.

They proposed that until improvements can be made by further research that a much-rounded value of 10 rads per WLM could be used as a *guide* to cancer related dose, probably to within a factor of 3 but possibly to not much better than a factor of 5 or so, for most of the expected conditions of mine air.

The work which has been done on developing models for estimating lung radiation doses resulting from inhalation of radon daughters has been very useful in defining the need for further studies which will give better definition of the various factors and thus reduce the uncertainties which exist. It has also indicated the lines of investigation which should be pursued. Eventually, sufficient information may be assembled to permit more precise statements to be made concerning the lung dosage which a miner will receive in an actual mine situation. This may require use of elaborate measurement procedures, or it may be found that mine conditions in general do not vary as widely as are now postulated. Variations in deposition resulting from varying breathing patterns will always exist, as will variations in lung clearance rates, either inherently or as the result of injury from a variety of environmental factors. These factors are also operative when the exposures are to non-radioactive toxic dusts.

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EVALUATION OF URANIUM MINE ATMOSPHERES

INTRODUCTION

Atmospheric aerosols in uranium mines are probably very similar to those in other hard rock mines in particle size distribution and in particle concentrations. The air-borne particles will consist of those produced by mining operations such as drilling, blasting and mucking. Also present will be carbon particles and condensation nuclei generated by diesel engines, and atmospheric particles carried in by ventilation air. Oil mists produced by drilling or by loading ammonium nitrate-fuel oil mixtures into drill holes will usually be present. Gas and vapors such as carbon monoxide, nitric oxides, aldehydes and complex hydrocarbons generated by diesel engines or blasting may also appear as contaminants. The noble gas ^{222}Rn and its short-lived daughters; RaA (^{218}Po), RaB (^{214}Pb), RaC (^{214}Bi) and RaC′ (^{214}Po) will always be present in the atmosphere of any underground operation, though usually in much higher concentrations in mines which produce uranium. Radon is continuously emitted into open areas from surrounding rock and broken ore or is carried in by ground water. Radon daughters are produced by radioactive decay of radon and thus are generated in mine atmospheres. The other members of the uranium family will also be present in air-borne dust produced by mining operations.

The main effort in evaluating potential health hazards in uranium mines has been directed toward measuring atmospheric concentrations of radon and radon daughters, and procedures for such measurements will be discussed in detail. Other substances, particularly those known or suspected to play a role in carcenogenesis, should not be overlooked, and will be considered later.

MEASUREMENT OF RADON

As stated above, radon is a normal constituent of the atmosphere and so methods for its measurement were developed very early. A spectrum of procedures are available suitable for measuring radon over a wide range of concentrations with a wide range of precision. Table 6 summarizes the various methods.

Of the methods listed in the table, only those in group III are of interest for measuring radon in uranium mine atmospheres, as the others are capable of greater sensitivity than is required. It is probable that some of the procedures in groups I and II could be modified for use with higher concentrations than those for which they were designed. The ionization chamber method was standard for many years, but for field work has been largely superseded by the alpha scintillations procedure because of the relatively simple equipment required by the latter. The alpha scintillation method and the "two-filter" method which will be described should be sufficient to meet the needs of most mining groups. The alpha scintillation procedure is capable of greater accuracy and is recommended for measuring rates of radon emanation from host rock or ore bodies, locating sources of contamination or determining radon in ventilation air to assist in deciding whether filtration of air to remove radon daughters is a feasible control method. The two-filter method has the advantage of giving a result in a relatively brief time, but because of its lower sensitivity and accuracy may only be useful in special situations.

The scintillation method for counting radon is the usual one employed by the United States Atomic Energy Health and Safety Laboratory and is described in the Health and Safety Laboratory Manual of Standard Procedures,[11] and by Lucas.[12] Its use in mines was described by Simpson et al[13] who employed it in surveys of Canadian mines. The common practice is to evacuate a number of scintillation bells and take them into the mine. The bell is opened to the atmosphere at the sampling location, drawing the air in through a filter to remove daughters and mine dust. If suitable field-type scintillation counters are available, they can be counted on the spot, otherwise a number of samples can be collected and counted later. If counting is delayed for three hours or more the daughters will be in

Table 6. SUMMARY OF METHODS FOR RADON DETERMINATION

Mode of collection	Theoretical basis	Counting method	Sensitivity[a]	Application	Advantages and/or disadvantages
I. Filter paper	Particulate daughter products collected on filter paper and their activity related to radon concentration. In most cases equilibrium assumed to exist between radon and its daughters.	(a) Alpha (2,3)	65 pCi/m^3	Field studies	Simple, rapid and inexpensive. Depends on radon-daughter equilibrium.
		(b) Beta (4,5)	15 pCi/m^3	Field studies — in studies where radon daughter equilibrium may not exist.	Useful for high dust loadings due to greater particle range. More complex than alpha counting.
II. Adsorption on charcoal bed.	Gaseous radon collected by adsorption from atmosphere by passage over activated charcoal at −78°C.	(a) Alpha (6)	3 pCi/sample	In studies of low levels of radon or where high sensitivity is required.	No assumptions as to equilibrium state are required. Equipment and technique complex.
		(b) Gamma (7,8)	120 pCi/m^3	Survey studies where direct determination of radon is required.	Requires no transfer of radon from collection to counting.
III. Entrapment of air containing radon.	Radon and daughters not isolated from air. Counted directly.	(a) Ionization Chamber (9)	1.0×10^4 pCi/m^3 by direct reading mode.	At relatively high levels.	Direct reading. Sensitivity can be increased by pulse height counting.
		(b) Alpha (10)	2.5×10^4 pCi/m^3	In areas of high concentration.	Least sensitive.

[a]Approximate concentrations for 10 percent counting errors at 90 percent confidence level using collection and analysis methods cited in reference.

From "Suggested Procedures for the Sampling and Measurement of Airborne Radon 222"

equilibrium with radon and sensitivity is increased. By correcting for decay of radon during the interval between sampling and counting, the radon content of the sampled air is calculated. Factors for growth and decay of radon and multiplicative factors are given in Table 7.

Commercial equipment is available for counting mine air in the field and has been found to perform satisfactorily. Very simple devices have been utilized, such as Erlenmeyer flasks coated internally with zinc sulfide phosphor as the scintillation bell, and a small pump or squeeze bulb to flush filtered air through the flask. An obvious way of obtaining a more representative sample of mine air for analysis is the collection procedure reported by Shearrer and Sill,[14] who used a small pump to inflate a mylar bag at a constant rate. Mylar is essentially impervious to radon and so an atmospheric sample integrated over a period of many hours can be obtained. A portion of this sample can then be withdrawn for analysis.

The two-filter method consists of passing mine air through a tube equipped with entrance and exit filters. The entrance filter removes all radon daughters and the exit filter collects the daughter atoms formed by decay of radon in the tube. From a count of the alpha activity on the exit filter, the radon content of the air can be calculated, by applying corrections for loses by diffusion to the walls of the tube and for growth and decay on the filter paper during and after

Table 7.

A. DECAY OF RADON (in Minutes, Hours, and Days).
B. GROWTH OF RADON FROM RADIUM (in Days).
C. MULTIPLICATIVE FACTOR FOR CORRECTION OF RADON ACTIVITY FOR DECAY DURING COUNTING (in Hours)

(Based on 3.825 days as half-life of radon)

Time	A. $e^{-\ t}$			B. $1\text{-}e^{-\ t}$	C. $\frac{t}{1\text{-}e^{-\ t}}$
	Minutes	Hours	Days	Days	Hours
0	1.000,00	1.000,00	1.000,00	0.000,00	1.000,00
1	0.999,87	0.992,48	0.834,27	0.165,73	1.003,72
2	0.999,75	0.985,01	0.696,00	0.304,00	1.007,54
3	0.999,62	0.977,60	0.580,65	0.419,35	1.011,39
4	0.999,50	0.970,25	0.484,42	0.515,58	1.015,16
5	0.999,37	0.962,95	0.404,14	0.595,86	1.018,98
6	0.999,25	0.955,71	0.337,16	0.662,84	1.022,83
7	0.999,12	0.948,52	0.281,28	0.718,72	1.026,65
8	0.998,99	0.941,39	0.234,66	0.765,34	1.030,51
9	0.998,87	0.934,31	0.195,77	0.804,23	1.034,36
10	0.998,74	0.927,28	0.163,33	0.836,67	1.038,23
11	0.998,62	0.920,31	0.136,26	0.863,74	1.042,10
12	0.998,49	0.913,38	0.113,68	0.886,32	1.045,97
13	0.998,37	0.906,51	0.094,84	0.905,16	1.049,88
14	0.998,24	0.899,69	0.079,12	0.920,88	1.053,79
15	0.998,11	0.892,93	0.066,01	0.933,99	1.057,69
16	0.997,99	0.886,21	0.055,07	0.944,93	1.061,61
17	0.997,86	0.879,55	0.045,94	0.954,06	1.065,54
18	0.997,74	0.872,93	0.038,33	0.961,67	1.069,49
19	0.997,61	0.866,36	0.031,98	0.968,02	1.073,44
20	0.997,49	0.859,85	0.026,68	0.973,32	1.077,40
21	0.997,36	0.853,38	0.022,25	0.977,75	1.081,37
22	0.997,24	0.846,96	0.018,57	0.981,43	1.085,35
23	0.997,11	0.840,59	0.015,49	0.984,51	1.089,34
24	0.996,99	0.834,27	0.012,92	0.987,08	1.093,33
25	0.996,86	0.827,99	0.010,78	0.989,22	1.097,34
26	0.996,73	0.821,77	0.008,99	0.991,01	1.101,36
27	0.996,61	0.815,58	0.007,50	0.992,50	1.105,39
28	0.996,48	0.809,45	0.006,26	0.993,74	1.109,42
29	0.996,36	0.803,36	0.005,22	0.994,78	1.113,47
30	0.996,23	0.797,32	0.004,36	0.995,64	1.117,52
31	0.996,11	0.791,32	0.003,63	0.996,37	1.121,58
32	0.995,98	0.785,37	0.003,03	0.996,97	1.125,66
33	0.995,86	0.779,46	0.002,53	0.997,47	1.129,74
34	0.995,73	0.773,60	0.002,11	0.997,89	1.133,83
35	0.995,61	0.767,78	0.001,76	0.998,24	1.137,94

Table 7.

A. DECAY OF RADON (in Minutes, Hours, and Days).
B. GROWTH OF RADON FROM RADIUM (in Days).
C. MULTIPLICATIVE FACTOR FOR CORRECTION OF RADON ACTIVITY FOR DECAY DURING COUNTING (in Hours) (Cont'd)

(Based on 3.825 days as half-life of radon)

Time	A. e^{-t}			B. $1-e^{-t}$	C. $\frac{t}{1-e^{-t}}$
	Minutes	Hours	Days	Days	Hours
36	0.995,48	0.762,01	0.001,47	0.998,53	1.142,05
37	0.995,36	0.756,28	0.001,23	0.998,77	1.146,17
38	0.995,23	0.750,59	0.001,02	0.998,98	1.150,30
39	0.995,11	0.744,94	0.000,85	0.999,15	1.154,44
40	0.994,98	0.739,34	0.000,71	0.999,29	1.158,59
41	0.994,85	0.733,78	0.000,59	0.999,41	1.162,75
42	0.994,73	0.728,26	0.000,50	0.999,50	1.166,92
43	0.994,60	0.722,78	0.000,41	0.999,59	1.171,09
44	0.994,48	0.717,34	0.000,34	0.999,66	1.175,28
45	0.994,35	0.711,95	0.000,29	0.999,71	1.179,47
46	0.994,23	0.706,59	0.000,24	0.999,76	1.183,68
47	0.994,10	0.701,28	0.000,20	0.999,80	1.187,89
48	0.993,98	0.696,00	0.000,17	0.999,83	1.192,12
49	0.993,85	0.690,77	0.000,14	0.999,86	1.196,35
50	0.993,73	0.685,57	0.000,12	0.999,88	1.200,60
51	0.993,60	0.680,42	0.000,10	0.999,90	1.204,85
52	0.993,48	0.675,30	0.000,08	0.999,92	1.209,11
53	0.993,35	0.670,22	0.000,07	0.999,93	1.213,38
54	0.993,23	0.665,18	0.000,06	0.999,94	1.217,66
55	0.993,10	0.660,18	0.000,05	0.999,95	1.221,95
56	0.992,98	0.655,21	0.000,04	0.999,96	1.226,25
57	0.992,85	0.650,28	0.000,03	0.999,97	1.230,56
58	0.992,73	0.645,39	0.000,03	0.999,97	1.234,88
59	0.992,60	0.640,54	0.000,02	0.999,98	1.239,21
60	0.992,48	0.635,72	0.000,02	0.999,98	1.243,54

the sampling period. The atmosphere sampled is passed through the tube at a constant flow rate for a given time, and the exit filter counted for a fixed time starting at some known time after the end of sampling. A discussion of the theory and procedure and tables listing the numerical values of the factors needed for the calculations are given by Thomas,[15] and by Thomas and LeClare.[16] The workers point out the precautions which must be taken. As the alpha activity on the exit paper is always lower than that of the ambient air, contamination must be avoided. It is recommended that leaks be avoided by pumping air through the tube, thus maintaining it under positive pressure. Glass-fiber papers should be used to minimize electrostatic charge which would increase contamination. Colman[17] has found that "Swedish Wool" glass wool is extremely effective as an entrance filter. The sensitivity of the method is a function of tube diameter, tube length, flow rate, sampling time, alpha background, counting efficiency and counting interval. For a 50 cm length, 3.6 cm diameter tube operated for 10 minutes at a flow rate of 10 liters per minute, and counted for 10 minutes starting at two minutes after end of sampling, Thomas estimates a sensitivity of 10 to 100 picocuries of radon per liter. The utility of this method would seem to be in those situations where information on the atmospheric radon

content was required in as short a time as possible. Examples would be when changes in ventilation are being made, and where sources of contamination are being sought.

MEASUREMENT OF RADON DAUGHTERS

Radium A, radium B, radium C and radium C′ occur in uranium mine atmospheres in varying ratios between each other and their parent radon. The extreme cases would be that of secular equilibrium (Rn:RaA:RaB:RaC:RaC′= 1:1:1:1:1) and where the atmospheres contained only radon and radium A. Either case occurs under unusual circumstances only. The first instance has been observed in a very large stope where the air change rate was too slow to measure, and the atmospheric concentration of fine particulates was high enough to minimize plate-out of daughters on walls. The second instance will occur downstream of a filter in the first few minutes after filtration.

The effect of ventilation rates on atmospheric concentrations of each of the daughters and thus of the ratios between them was first developed by Trivoglou and Ayer.[18] The curves in Figure 6 show how the atmospheric concentrations change with increasing air-change rates.

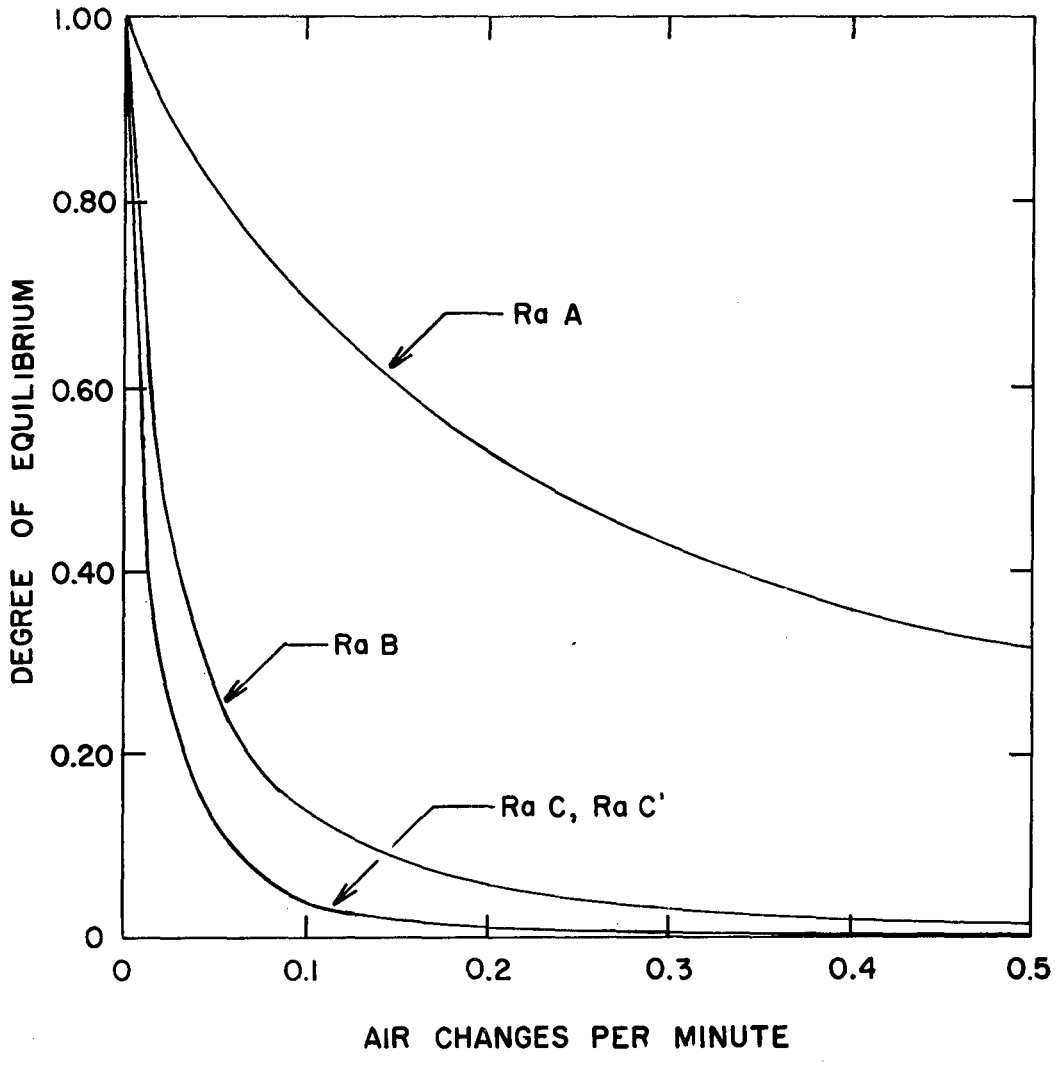

Figure 6: Effect of ventilation rates on ratios of atmospheric concentrations of radon daughters (activity basis). (Tsivoglov and Ayer[18])

In actual mine conditions, these theoretical curves are seldom observed because of contamination of ventilation air in its passage through the air course or by aspiration of contaminated air from adjacent areas. This subject will be discussed further in the section on control.

Information on the atmospheric concentrations of the individual radon daughters is not often utilized in control work. However, it is important to those who are studying radiation dosages.

Methods for measuring the air activity of these elements have been studied extensively and several different procedures are available.

The most direct approach to determining atmospheric concentrations of radon daughters is that reported by Martz et al.[19] These workers used a solid state alpha spectrometer and a multichannel analyzer system to count the RaA and RaC′ activities on a filter at 5 and 30 minutes after sampling. The variations between replicate samples was much less than variations obtained when the same samples were analyzed by the Tsivoglou method. Table 8 shows the comparisons between the two methods.

It is apparent that the alpha spectroscopy method has lower standard deviations, and would give much more reliable results both for relative and absolute concentrations. The equipment is relatively complicated and expensive and not suitable for field work at this time.

Other methods for measuring absolute amounts of radon daughters in mine air are based upon counting at fixed intervals after sampling the alpha activity deposited on a filter paper and using these values in a series of simultaneous equations. This approach was reported by Tsivoglou, Ayer and Holaday,[20] and has since been refined and modified by several others. A review of this subject is given by Thomas[21] who recalculated the values of the coefficients used and presented the basic equations. The later feature makes this reference particularly useful.

A mathematical method employing weighted-least squares for the analysis of air samples for radon daughters was developed by Raabe and Wren.[22] It employs observations of the total alpha particle count from the filter paper during various periods of time rather than count rates at selected times. The procedure is more accurate than any of those using simultaneous equations and yields estimates of error. The authors recommend it particularly for research work. The method was tested in a uranium mine using portable equipment to count the filters underground. The instrument which is described used a combination zinc sulfide phosphor, photo-multiplier tube and scaler.

The major difficulty with all the methods is the requirement for an early count which means that portable scalers or recording count rate meters that can be used underground must be available. Such equipment has been used by Billiard and Pradel in uranium mines in France. Air is drawn through a filter paper and the activity continuously counted by a scintillation detector and a count rate meter. The counts are fed to a recorder which plots a build-up curve and, after sampling ceases, a decay curve. The curve is matched with a series of computer-drawn curves and the best fit selected.

Reports of extensive series of measurements are scanty, most of such data being given in PHS Publication 494.[23] The results of one other study are listed in Tables 7 and 8. Gusarov and Lyapidevsky[24] also reported that in Russian mines the proportion RaA:RaB:RaC varied within broad limits; however, the maximum deviation from equilibrium did not exceed 1:0.3:0.1.

A rapid and simple method for determining the ratios of the isotopes, but not the absolute activities was described by Harley.[25] A series of graphs was prepared which could be used for

Table 8. COMPARISON OF EXPERIMENTAL AND THEORETICAL STATISTICAL ANALYSES BY THE TSIVOGLOU AND SPECTROSCOPIC METHODS.

	Tsivoglou method			Spectroscopic method		
Isotope	Average estimated concentration	Experimental standard deviation	Theoretical standard deviation	Average estimated concentration	Experimental standard deviation	Theoretical standard deviation
RaA	1321	28.6	35.0	1382	7.8	4.0
RaB	750	12.6	10.9	744	12.0	8.5
RaC	532	26.8	24.0	484	14.1	11.0

From Martz, et al.[19]

estimating ratios of the activities of RaA, RaB, and RaC from alpha counts taken at 5, 15 and 30 minutes after end of sampling. This procedure eliminates calculations and probably would give sufficiently precise results to be useful for control work.

MEASUREMENT OF THE WORKING LEVEL

The term "working level" was first introduced in PHS Publication 494. It was used to describe the level of atmospheric concentrations of radon daughters which was recommended as a guide for control purposes until sufficient information was accumulated to justify establishing a Threshold Limit Value. The term is now ensconced in the literature as a unit describing the latent alpha energy inherent in a liter of air containing 100 pCi of RaA, 100 pCi of RaB and 100 pCi of RaC. The precise definition now is: One working level is any combination of radon daughters in one liter of air that will ultimately release 1.3×10^5MeV of alpha energy during decay to ^{210}Pb(RaD). This unit is a quantity which can be measured either by field or laboratory equipment and so has been widely used. As pointed out previously, it is not consistently correlated with potential biological effect and thus should be used with reservations for estimating relative degrees of hazard. However, alternatives are not appealing. Routine measurements of atmospheric concentrations of the individual isotopes are not feasible, and if made would be difficult to interpret in terms of potential biological hazard without knowledge of the size distribution of the particles to which they were attached.

The concept of expressing atmospheric concentrations of radon daughters in terms of latent alpha energy content was proposed by Kusnetz[26] who developed a procedure for evaluating this quantity. The basic mathematical treatment was not given in detail in Kusnetz's report. Shalaygev,[27] however, included a complete derivation of the basic equations in his discussion of the maximum permissible concentration for radon daughters.

A number of different procedures for measuring working levels have been devised, the majority of which are based on drawing air through a filter paper and subsequently counting the alpha activity on the paper. Table 9 lists several methods which have been used in Russia. Rolle[28] developed a technique which is used in South Africa, and a procedure utilizing beta counting of the filter paper was employed by Ritter[29] in radiation surveys of Bavarian mines. An "instant working level meter" which has attractive features was devised and used by Schroder.[30]

Thus, a wide variety of procedures are available for evaluating atmospheric concentrations in terms of the working level. The choice of method will depend on the intended use of the data. For guidance in control work, a method which will yield an answer in a few minutes with some sacrifice of accuracy may be the most desirable. For purposes of collecting data to be used in compiling exposure records where more accuracy is desirable, a method which is more time-consuming may be required. The procedures described in detail will be adequate for most of the situations encountered in uranium mines. It is emphasized that the details of the methods must be followed to attain the degree of accuracy and precision of which they are capable.

KUSNETZ METHOD

This procedure is taken from the American Standard for Radiation Protection in Uranium Mines N13.1-1970, Appendix C.

General

The atmospheric concentrations of radon daughters may be measured by drawing a known volume of air through a suitable filter paper and counting the alpha activity on the paper at a measured time after sampling. From these data, the radon daughter concentration in the air sampled may be calculated.

Equipment Criteria

Equipment for carrying out the sampling and measurements is available commercially. The procedures set forth in this standard are not based on the use of any specific make of any piece of equipment.

Filter Type. Glass fiber, or membrane filters with pore sizes on the order of 0.8 microns, should be used. A water resistant filter material should be used in wet mines. These filters show a penetration into the paper (with consequent self-absorption) of less than 10 percent and are rugged enough for field use. Other filters may be used provided that self-absorption of alpha particles and other characteristics are evaluated for the particular atmosphere to be sampled.

Air Sampling Pump. A pump equipped with a suitable metering device and capable of pulling

Table 9. GROUP II. METHODS FOR DETERMINING LATENT ENERGY OF RADIATION OF THE DAUGHTER PRODUCTS OF RADON SEPARATED FROM A UNIT OF VALUE OF THE AIR UNDER INVESTIGATION.

Method	Total error statistical and methodological	Time of sampling	Time of measurement	Time of mathematical treatment of results	Equipment
II-1. Method of the total count.	Methodological error ± 3.5.	Not fixed.	1 hr. after the end of filtration.	Several minutes	An adapter (of Gusarov and Lyapidevskii) to the scintillation counting attachment to the B-3 system, rheometer, air blower.
II-2. Equilibrium method.	Methodological error ± 3.5% and statistical 1.4% at a level with the limits of permissible concentration of the daughters products of radon in the air (3×10^{-11} curie/l for each isotope individually).	Not fixed.	Several minutes or any desired time upon reaching the equilibrium straight line. To reach the straight line takes 2 hrs by using the accelerated method of Gusarov and Lyapidevskii, (1960).	Several minutes	Same as above.
II-3. Method of a single measurement of the filter activity 40-60 min. after sampling.	Methodological error within the limits 10-15% and statistical 18.5% at a level of the limited permissible concentration of the daughter products of radon in the air under study.	Rigidly fixed (5 min.)	For several min. after 40-60 min. upon completion of sampling.	Several minutes	Filter, filter holder, air blower, scintillation counting attachment, conversion device.
II-4. Method of the total count of the filter activity from the 7th through the 10th min. after the end of filtration.	30% with RaA concentration in the studied air at 5×10^{-12} curie/lit.	Rigidly fixed (5 min.)	10 min.	Several minutes	Portable equipment not described.

Table 9. GROUP II. METHODS FOR DETERMINING LATENT ENERGY OF RADIATION OF THE DAUGHTER PRODUCTS OF RADON SEPARATED FROM A UNIT OF VALUE OF THE AIR UNDER INVESTIGATION. (Cont'd)

Method	Total error statistical and methodological	Time of sampling	Time of measurement	Time of mathematical treatment of results	Equipment
II-5. Method of a single measurement of the filter activity 20 min. after termination of sampling.	Up to 50%	Not fixed.	For several min. after 20 min. upon completion of sampling.	Several minutes	Filter, filter holder, rheometer, air blower, scintillation transmitter, conversion device.

From Gusarov and Lyapiderskii: Gig. i San.[24]

not less than 2 liters of air per minute through the filter shall be used. Several pumps which provide flow rates of from 2-10 liters per minute are available. A flow of 10 liters per minute through a 1-1¼ inch filter gives a face velocity of about 30 centimeters per second. Available data indicated that the recommended filters are sufficiently retentive at rates of only a few centimeters per second. For use in the mine, the pump chosen should be completely portable and light in weight and, if battery operated, should have sufficient battery life to last a working day. Since the expected dust loading in mine air is less than a milligram per cubic meter, this will not cause any problems in sample collection or measurement.

Counting Equipment. The alpha activity on the filter shall be measured on a device sensitive enough to measure 0.3 working levels after the maximum decay time of 90 minutes. The equipment should be sufficiently rugged and humidity proof to permit operation directly in the mine. One class of counter which meets these criteria is the scintillation counter using zinc sulfide as the phosphor.

Calibration of Equipment

Calibration of Pumps. Pumps and filter train shall be calibrated together as a single piece of equipment for air flow after receipt of the pump from the manufacturer and at least quarterly thereafter or whenever any abnormal operation of the pumps and filter train is apparent. Almost all pumps are manufactured and originally calibrated for free flow at sea level, and therefore must be recalibrated before use at approximately the altitude at which they will be used. Filters and filter holders used in calibration shall be the same type as will be used in field work. A wet-test meter is often available at the local gas company. The test meter is always used ahead of the filter holder and pump to ensure measuring unexpanded air.

Calibration of Counters. Counters shall be calibrated after receipt from the manufacturers. Alpha survey meters must be calibrated against radium C′ since most of these instruments are somewhat energy-dependent. A source of radon (finely crushed uranium ore in a steel drum is a satisfactory source) and a laboratory alpha counter of known alpha efficiency are required. Radon daughters are collected on a filter paper by drawing air from the drum through the paper. The paper is allowed to stand for 15 minutes to permit radium A to decay. The paper is then counted in the laboratory counter and by the survey meter. The time of each count is recorded and a decay curve drawn, using the laboratory counter data. From this curve, the disintegrations per minute corresponding to the time for each meter reading can be determined, and calibration curves drawn. A working standard of uranium foil, a plated uranium source, or a thorium 230 source which has been calibrated in a 2 pi counter should be used to check the counter before each day's use. If significant deviations from previous checks are exhibited, the counter and/or the check source shall be recalibrated.

Self-Absorption of Filters

Filters other than those specified shall be calibrated for self-absorption and the measurement corrected for the self-absorption. The procedure for this calibration is as follows:

(1) Collect radon daughters on the filter and count the alpha activity. Wait at least 15 minutes after sampling for ^{218}Po activity to decay. This is count C_1.

(2) Turn the paper over and count the reverse side. This is count C_2.

(3) Cover the front side of the sample filter with a similar unused filter and count again. This is count C_3.

(4) Calculate the percent self-absorption from the equation:

$$\frac{C_2 - C_3}{2C_1 + C_2 - C_3} \times 100 = \% \text{ self-absorption}$$

The following procedure should be used in sampling for the purpose of evaluating the need for, and effectiveness of, control procedures or measuring the mine atmosphere for exposure estimates. Other procedures may be used if they are capable of developing information of essentially comparable quality.

(1) Draw a sample through the filter for 5 minutes at the rate of at least 2 liters per minute.

(2) Alpha count the sample any time from 40 to 90 minutes after the end of sampling. Convert the alpha particle counting rate in counts per minute (cpm) to a disintegration rate in disintegrations per minute (dpm) using the calibration curve for the meter.

(3) Divide the alpha disintegrations per minute (dpm) by the volume of air sampled in liters. The results will be the alpha activity expressed as disintegrations per minute per liter (dpm/1).

(4) Divide the dpm/1 by the factor obtained from the accompanying graph (Figure 7) corresponding to the elapsed time between the end of sampling and counting to give the atmospheric concentration of radon daughters as a fraction or multiple of the working level.

HARLEY AND PASTERNACK METHOD

General

Harley and Pasternack[31] expanded and modified the Kusnetz method to permit use of different sampling times and to reduce errors in measurement of the working level in atmospheres where the equilibrium ratios lie outside the range specified by Kusnetz. This procedure is more flexible and is particularly applicable for evaluation of filtered air. In these situations, a large air sample may be required and extreme off-equilibrium conditions may exist.

The article presents graphs for obtaining factors for converting from alpha dpm per liter to working levels for 1, 5 and 20 minute samples for ranges of equilibrium conditions from 1:1:1 to 1:0, 01:0.0001. Use of an average factor where equilibrium conditions are unknown will result in a maximum error of ± 25 percent. Use of the average factor for each of the two ranges selected will give a maximum error of ± 13 percent. The statements on equipment criteria, calibration of counting equipment, and self-absorption of filters detailed in the Kusnetz method apply.

Procedure

The recommended procedure is:

(1) Draw a sample through the filter for 1, 5 or 20 minutes as desired.

(2) Measure the alpha activity on the filter at 40 minutes after end of sampling for 1 and 5 minute samples, 30 minutes after end of sampling for a 20 minute sample.

(3) Convert the alpha activity to alpha dpm per liter samples.

(4) Divide by an average factor of 125 if the equilibrium range is unknown; if the equilibrium range is known to be between 1:1:1 to 1:0.1:0.0:1, by 142; by 115 if the range is from 1:0.1:0. to 1:0.01:0.001.

ERRORS IN MEASUREMENT OF WORKING LEVEL

Studies of errors in measurement of the working level were reported by Loysen.[32] While these studies were concerned with the Kusnetz method, the findings are applicable to all methods. The report investigated errors in: air sample volume, counting, and computation. Each of these groups contain several sources of possible error; however, none would have serious effect unless several errors chanced to be in the same direction. The sampling precision error was a function of working level, increasing at small WL values. However, even at 0.3 WL the variation was only 13 percent. The accuracy was determined by ap-

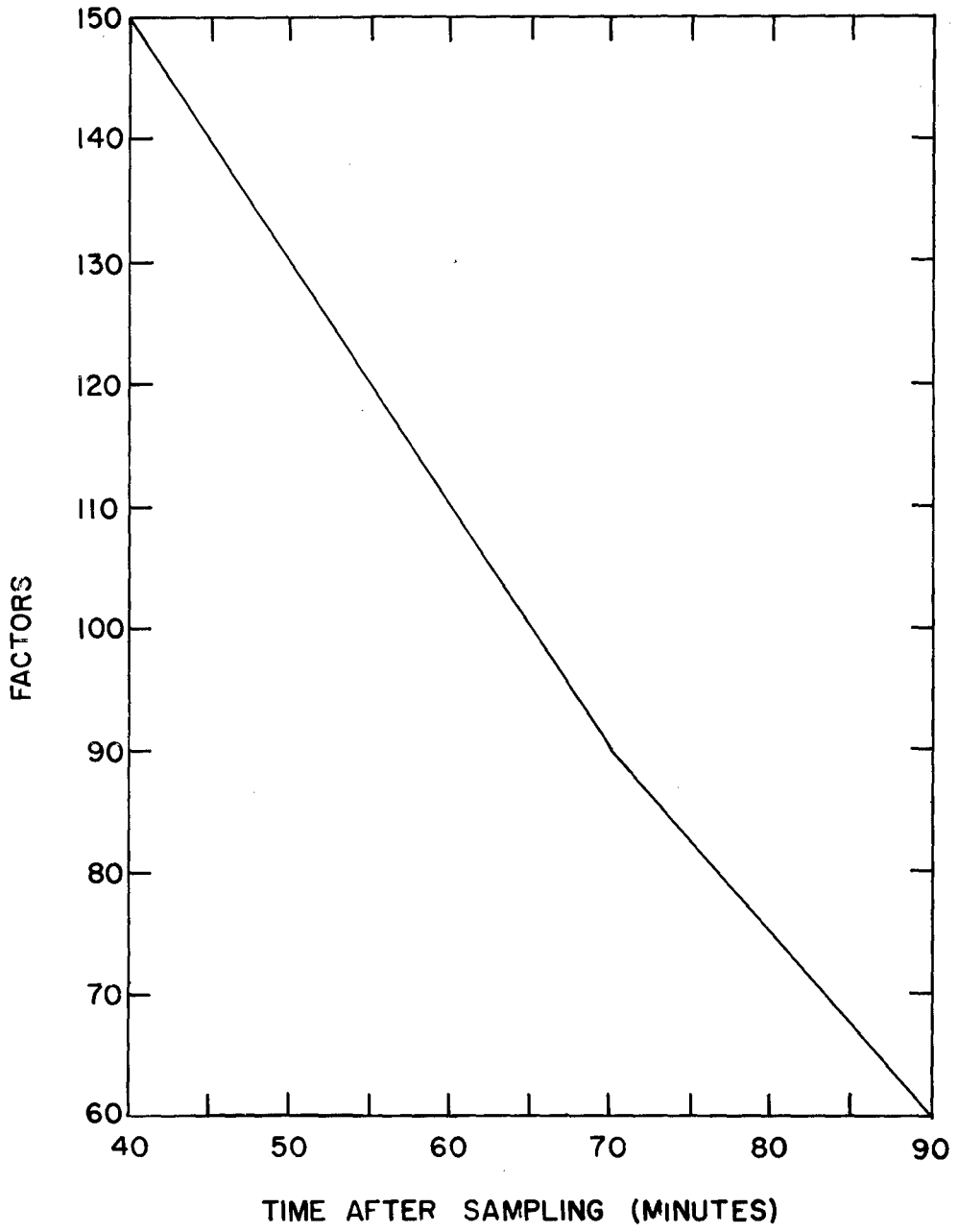

Figure 7: Factor-time relationship for use in determining atmospheric concentration of radon daughters in terms of working levels by the Kusnetz procedure. (Kusnetz[26])

plying the Kusnetz and Tsivoglou methods to the same samples. When one value was plotted against the other, the least squares fit line had a slope of 0.994 with a correlation coefficient of 0.996. These results illustrate the accuracy that can be obtained using well-calibrated equipment and reasonable precautions.

LONG-LIVED ALPHA EMITTERS

Uranium ore dust is dispersed into the atmosphere by mining operations. This dust contains the alpha-emitting elements ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, and ^{210}Po. Some of the dust is inhaled and deposited in the lung. Very few studies of the atmospheric concentrations of these elements

have been reported. The most extensive work on this subject is done in France where the uranium mines are monitored routinely to determine atmospheric concentrations of long-lived alpha emitters. The monitoring procedures and sampling and counting equipment used in the French program were described by Couix and Pradel at the Vienna Symposium.[33] Samples of air-borne dust are collected by drawing air through a filter paper with a compressed air ejector. The short-lived radon daughters are allowed to decay and the alpha activity on the paper are counted using a zinc sulfide-coated clear plastic disk placed on the filter and a photo-multiplier tube as a detector. The entire counting program is automated to permit handling the large volume of samples. A maximum permissible concentration of 36 alpha disintegrations per minute per cubic meter of air has been established by France. At the Vienna Symposium, Fusamura and Misawa[34] also reported measurements of uranium in air-borne dust in Japanese uranium mines. The quantities found were small, ranging from $0.138 - 1.050 \times 10^{-13}$ microcuries per cubic centimeter. Compared with the maximum permissible concentration for uranium (6×10^{-11} microcuries per cubic centimeter) these are low concentrations. Measurements of urinary uranium concentrations in American uranium miners made at the Western Area Occupational Health Laboratory have also indicated that exposure to uranium was minimal, the vast majority showing concentrations of less than 10 micrograms per liter. All of the studies mentioned were done in mines where the ore was the usual low grade (about 0.3 percent U_3O_8 or less). As the potential health hazards created by exposure to ore dust in uranium mines should be similar to those created by exposure to ore dust in uranium mills, the Maximum Permissible Concentration (MPC), and evaluation procedure used in the latter situations should apply. The A.E.C. permits a procedure for estimating the atmospheric concentrations of the mixture of long-lived alpha emitters by measurement of uranium only,[35] and the MPC, is 75 micrograms of uranium per cubic meter of air. This number is based on these assumptions: there is secular equilibrium between the long-lived members; the critical organ is the lung; and the biological half-lives in the lung for the elements of interest are equal. This MPC of 75 ug/m^3 means that for an air-borne dust containing one percent uranium, a total atmospheric dust concentration of 7.5 mg/m^3 would be permitted. If the dust contained 50 percent free silica, a dust loading of 0.2 mg/m^3 would be permitted by the TLV for silica dusts. Thus, control of the silica hazard would insure control of hazards from long-lived alpha emitters.

MEASUREMENT OF UNATTACHED DAUGHTERS

The special influence of unattached daughter atoms on lung radiation dose was discussed in the section on dosimetry. It is desirable to know the fraction of daughter atoms that exist unattached in mine atmospheres and the ranges which may be expected in varying mine conditions. However, measurement of this quantity is not simple nor is the data obtained easily interpreted. It is probable that there is no sharp differentiation between atomic sized particles and larger sized particles but that a spectrum of sizes of fine particles exists in the atmosphere ranging upward from nearly atomic size. For example, Clark and Whidby[36] in a study of atmospheric particles found increasing numbers of particles with decreasing size down to 0.005 micron, the smallest size measured. Holleman, [37] reporting studies by the Colorado State University group, concluded that even in extremely dusty mine atmospheres, the alterations in particle size distribution and number concentration of particles produced by mining operations were insignificant in relationship to the natural aerosols. This general statement would probably not hold for areas where diesel engines were operating or for remote areas with very low air change rates. In the former instance, the diesel engines would inject very large numbers of ultra-fine particles into the immediate area, and in the latter the particles would agglemerate and settle out. Table 10 lists the results of a study of atmospheric particles by Kirichenko, et al[38] in Russian mines. The authors stated that the data is only approximate because of instrumental limitations. However, they are interesting.

Many factors affect the value of the fraction of radon daughter products which will be present as free atoms. Among these are: the number concentration of particulates; the number concentration of radon daughter atoms; the equilibrium ratios between the daughters, and electrostatic charges on the atoms and particles. With all these variables operating it is not surprising that measurements of the fractions of free atoms have found a wide range of values. Among the

Table 10. COUNTED CONCENTRATION OF AEROSOLS IN MINE AIR

Site of measurement	Mining operation	Particles per cm^3	
		Particles of radius> 10^{-7}cm	Particles of radius> 10^{-5}cm
MINE NO. 1			
Intake ventilating shaft	—	9×10^5	57
Head of the downcast (fresh) air	—	7×10^5	70
Downcast air at a distance of 300 m from the entrance.	—	1.6×10^5	240
Subdeposit drift at breakage spaces	—	2.4×10^6	460
Breakage space No. 19	Dry drilling	2.9×10^6	9.8×10^4
	Wet drilling	9.4×10^5	3.2×10^3
Breakage space No. 20	Scraping	2.5×10^5	2.8×10^3
Breakage space No. 21	No operations	7.3×10^4	1.3×10^3
Upcast air	—	1.7×10^5	3.5×10^3
MINE NO. 2			
Downcast air	—	8.0×10^5	<10
Upcast air	—	1.0×10^5	500

From Kirichenko, et al.[38]

reports of measurements in mines are those of Billiard, et al[39] in France, Kirichenke, et al[38] in Russia; George and Breslin,[40] George and Hinchliff,[41] Holleman, et al,[37] Craft, et al,[42] and Raghavayya and Jones[43] in the United States. The results of one series of measurements are given in Table 11.

A variety of methods and instruments were used in these surveys and it is probable that a large part of the differences in results are due to differences in the procedures used. The measurements of George and Hinchliff were made with a sampler which collected free atoms by diffusion, while those of Chapius, et al were made with an electrostatic precipitator. The median and mean values for the fraction of free atoms which were reported by the two groups were surprisingly similar. George[44] describes a wire screen method which is similar but not identical to the procedure employed by Ragavayya and Jones with the primary difference being in the size mesh screens utilized. It is possible that the 120 mesh screen used by Ragavayya and Jones would collect not only individual atoms, but also recoil atoms attached to a minute fragment of a particle while the 60 mesh screen employed by George would collect only individual atoms.

An alternative approach suggested by Raabe[45] is based upon a theoretical treatment of the processes of attachment of radon daughters to aerosols. The principle which he developed predicts that attachment is proportional to surface area of the aerosol particles for all particle sizes and all but extremely high concentrations of radon. A hypothetical formula for aerosols in uranium mines was developed which can be used to calculate the expected fractions of unattached radon daughters. Table 12 shows the results of these calculations for one case using this hypothetical aerosol and one equilibrium condition.

This approach may be useful as it involves only measurements of the number concentration of particles and the equilibrium ratio. Further studies of mine atmospheres are needed to test this procedure.

In summary, methods are now available for measuring free atoms in uranium mine atmospheres but none are suitable for routine use. What constitutes "free atoms" is somewhat uncertain. Perhaps terms such as "highly mobile" or "highly diffusible" would more closely express the intended meaning.

Table 11. PROPORTION OF THE FREE ATOMS OF THE DAUGHTER PRODUCTS OF RADON AT DIFFERENT POINTS IN THE MINE.

Sampling site	Condition	Fraction of free atoms		Ratio of the radioactive isotope in air A:B:C:
		radium A	radium B	
Breakage space No. 1	No operations	0.52	0.08	1:0.72:0.18
	Wet drilling	0.19	0.08	1:0.44:0.11
Breakage space No. 2	Top breaking	0.21	0.06	1:1.1:0.67
	Scraping	0	0	1:0.75:0.30
	Wet drilling	0.20	—	1:1.2:0.86
Upcast air from breakage space No. 3 ventilated with fresh air, 10 m from the jet outlet	—	0.88	0.51	1:0.32:0.15
Upcast air from breakage space No. 3,400 m from the outlet	—	0.34	0	1:0.62:0.47
Upcast air from breakage spaces Nos. 1, 2 and 3 after mixing	—	0.19 0.36	0.03 0	1:0.71:0.31 1:0.60:0.42

From Kirichenko, et al.[38]

Table 12. RADON DAUGHTER PARAMETERS FOR HYPOTHETICAL MINE ATMOSPHERE FOR VARIOUS AEROSOL CONCENTRATIONS n per cc*.

N	fa	fb	fc
10^3	0.85	0.54	0.40
5×10^3	0.52	0.14	0.04
10^4	0.36	0.07	0.01
5×10^4	0.10	0.01	
10^5	0.05		
5×10^5	0.01		

*Activity ratios of daughters to radon are 1:0.6:0.3; (residence time of air=40 min) (recoil fraction of RaA=0.5, recoil fraction RaB=0.)
After Raabe[42] Health Physics.

DIESEL ENGINE COMBUSTION PRODUCTS

The term "diesel engine combustion products" includes a number of substances. Such compounds as oxides of nitrogen, carbon monoxide and aldehydes are usually measured in routine surveys of the quality of mine air. Of particular interest in uranium mines are the polycyclic hydrocarbons contained in the benzene-soluble fraction of the solid combustion products. These compounds are absorbed on fine carbon particles which are respirable. Some of the polycyclic hydrocarbons are known or suspected carcenogens or possibly co-carcenogens, thus it would be desirable to measure the quantity present in mine atmospheres.

The American Conference of Governmental Industrial Hygienists has proposed a tentative Threshold Limit Value (TLV) of 0.2 milligram per cubic meter (mg/m^3) for the benzene-soluble fraction of atmospheric contaminants. The procedure for measuring atmospheric concentrations of this fraction is quite simple. Air is drawn through a silver membrane or organic membrane filter; the filter extracted with benzene in a Soxhlet extractor; the benzene evaporated off in a tared container and the residue weighed. A balance sensitive to 0.01 mg. is required.

OIL MISTS

The TLV for oil mists (sampled by a method that does not collect vapors) is 15 mg per cubic meter. Operations such as loading ammonium-nitrate fuel oil mixtures into holes, or drilling can produce appreciable atmospheric concentrations of oil mists. Prudence dictates that the extent of this possible problem should be evaluated. One procedure is to draw air through a glass wool bed

contained in a drying tube. The oil is eluted from the wool with petroleum ether. The petroleum ether solution is filtered into a tared dish, the solvent evaporated and the residue weighed.

SILICA DUST

Silica dust is a well-known hazard in mine atmospheres, and evaluation of this contaminant should be a routine procedure. It is discussed in this chapter for the following reasons:

(1) Animal experiments by LaFuma and Medjedovic[43] and by Kushneva[44] showed that exposure to mixtures of radon and silica dust produced greater fibrotic changes in the lungs than those exposed to radon or silica separately.

(2) Use of large amounts of ventilation air may dry out some mine areas thus increasing the possibility of dispersion of dust. Additionally, the air velocity in air courses may become great enough to re-suspend settled dust.

(3) Concentration on radiation problems may create a tendency to reduce surveillance of silica dust concentrations.

Atmospheric concentrations of silica dust may be evaluated either by particle counting or by a gravimetric method. The particle counting procedure is described in PHS 614,[45] and the gravimetric procedures is discussed by Ayer, Sutton and Davis.[46] The latter method has the advantage of sampling over longer time periods and being less arduous than is particle counting.

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CONTROL OF EXPOSURE TO RADON AND RADON DAUGHTERS

INTRODUCTION

Insuring that uranium miners are not overexposed to radon and radon daughters is an extremely difficult task which requires a comprehensive program to accomplish. This section will discuss the features of such a program, present digests of the detailed reports which have been made, and include material obtained from mine ventilation officers which may not be generally available.

The U.S. Bureau of Mines[1] and Beranek[2] have prepared extensive discussions of the problems of radiation protection in uranium mines. The manual by Rock and Walker considers conditions in American uranium mines, and that of Beranek is a compilation of Russian practices. Both of these publications are excellent sources from which much of the material in this section is drawn. They should be referred to for detailed information.

The contents of a program for controlling radiation exposure of miners as listed by Beranek are:

(a) Comprehensive action to normalize the mine atmosphere;
(b) Individual protection measures;
(c) Organizational procedures for interchanging workers between relatively safe and unsafe working areas;
(d) Systematic monitoring.

Of these items, control of atmospheric concentrations of radon daughters is the most important, and to be successful, a control procedure must consider such factors as: careful planning of the methods of exploring and working the deposits; integration of the general ventilation plans with the plans for ore extraction; and procedures for reducing release of radon into active mine areas. There is no typical uranium mine and each operation has some features peculiar to itself. The general procedures and basic information discussed in this section will often require adaptation before use in particular situations.

PLANNING OPERATIONS IN URANIUM MINES

Essential factors to be considered in planning uranium mining operations are discussed in detail by Beranek. The first consideration, to limit radon release, limits the working methods which can be used. The area of exposed ore should be kept as small as possible, from both health and economic standpoints. Every ore face requires ventilation to remove the radon, and this can be very costly. Table 13 lists the annual air requirements and costs of electric power for ventilation in several areas of three Russian mines.

Similar data for American mines are not available, but Table 13 illustrates the economic desirability of keeping the area of exposed ore at a minimum.

Wherever possible, deposits should be explored by drill holes from the surface rather than by underground workings. This obviates exposing ore faces before the time for removal. If the ore body can be delineated sufficiently, haulageways and air courses should be driven through country rock. Unfortunately, in districts such as the Uravan Mineral Belt, the ore deposits are so irregular that systematic planning is often an ideal rather than an achievable approach. All systems of extracting ore which are employed in general mining practice have been used for working uranium deposits. To reduce radon release plans should be made to minimize the number of ore faces existing simultaneously; to limit underground storage time of broken ore; to avoid spillage of ore in transportation; to minimize handling of ore; and to remove ore as completely as possible.

Both Rock and Walker and Beranek discuss the above points. Their importance is obvious, and yet they are frequently overlooked. Particular emphasis is given to the desirability of utilizing the method of retreat mining towards intake air. In this procedure the deposits are worked from the boundaries towards the intake shaft.

Table 13. ANNUAL AIR REQUIREMENTS AND COST OF ELECTRIC POWER NEEDED TO VENTILATE 1 m² OF THE SURFACE OF A WORKING AS A FUNCTION OF SPECIFIC RADON RELEASE

Specific radon release Ci/sec/m²	Qualitative designation of the emanation	Annual air requirements (m³/year)	Annual cost of electric power (roubles/m²) in mines		
			1	2	3
1.0×10^{-11}	Weak	3,150	0.034	0.060	0.108
1.0×10^{-10}	Moderate	31,500	0.342	0.598	1.08
5.0×10^{-10}	Strong	157,500	1.71	2.94	5.38
1.0×10^{-9}	Very strong	315,000	3.42	5.98	10.76
5.0×10^{-9}	Extremely strong	1,575,000	17.1	29.4	53.8

From Beranek[2]

By this means highly contaminated air is kept downwind of the working areas and thus presents no health problems. Bates and Walker also recommend that on-shift blasting be kept at a minimum. This recommendation is based on Evans'[3] report on the interstitial radon content of ore, where he estimated that one cubic yard of ore grade rock in place, with 20 percent porosity, could contain 150×10^6 pCis of radon. Therefore, it is possible that relatively large quantities of radon could be released in a small space by blasting, thus producing temporary high atmospheric concentrations.

In summary, in planning mine operations and working procedures, every effort should be made to design out sources of contamination. Reducing emission of radon may well be less costly than the measures required to remove contaminated air.

PRINCIPLES GOVERNING THE BEHAVIOR OF RADON

Radon produced by decay of radium contained in ore or sub-ore bodies will diffuse in all directions from the source. It will be released by diffusion into open areas or be carried in by convective air currents or hydraulic pressure caused by movement of ground water. Schroeder et al[4] measured radon concentrations in soil gases in several different environments and from these data, measurements of radon flux at the soil surface, and soil porosity computed the diffusion coefficient D. The results are listed in Table 14.

Table 14. VALUES OF RADON DIFFUSION COEFFICIENT OBSERVED IN NATURALLY-OCCURRING SOILS

Soil type	Soil condition	Region of measurement	Diffusion coefficient (cm²/sec)
Glacial debris (Lincoln, Mass.)	Moist, matted grass ground cover S = 40%	Surface flux and Rn concentration gradient in upper 12″ of soil	0.02
Consolidated sandstone (Grants, New Mexico)	Mine tunnel moderately dry S = 25%	Flux into mine area Rn concentration gradient in initial 5′ of rock surrounding mine	0.03
Alluvium (Yucca Flat, AEC-NTS)	Dry	3′ to 9′ in alluvium	0.036
Alluvium (Yucca Flat, AEC-NTS)	Very dry, powdery, little-to-no ground-cover S = 25%	Surface flux and Rn concentration gradient in upper 12″ of alluvium	0.10

S=soil porosity=ratio of void volume to total volume of soil (i.e., solids plus voids)
From Schroder, et al.[4]

The average result of 0.03 cm^2/sec was estimated by these workers to be a fair approximation of the true value for a relatively dry, porous medium. The diffusion coefficient is one factor governing specific radon flux (pCi/sec/m^2) into a mine area. Other factors will be the concentration of radium in the rock surrounding open areas, the degree of fracturing of the rock, porosity, convective air currents, and movement of groundwater. Interaction of these factors results in wide variations in radon flux. Table 13 shows a variation by a factor of 500 in Russian mines, for example. An average emanation rate of 5×10^{-12} Ci/sec/m^2 (one-half the lowest Russian value) has been reported for one Canadian mine.[5] This reference quotes measurements by Schroeder in American mines as being 100 times this value. Emanation rate measurements made by the United States Public Health Service[6] were reported as "atoms per minute per 1000 ft^3 of stope volume" and so are not comparable. The forty-fold variations in total radon flux which were found indicated conditions which could be encountered. Tsivoglou and Ayer[7] studied the effect of ventilation on radon concentrations in mine areas. The basic equation which they developed is: $Q\ (\text{inf.}) = \frac{R}{V}$

Q is the radon concentration after ventilation for a sufficiently long time to reach a steady state concentration; R is the radon emanation rate in atoms per min (or pCi/min); and V is the ventilation rate.

Note that the volume of the area need not be known to determine the radon flux. It is only necessary to measure the steady state concentration of radon and the ventilation rate. Volume terms in Q and V must be expressed in consistent units, and the ventilation rate must be high enough so that the residence time of radon in the area is short compared to its half-life. At any practical ventilation rate, this condition will be fulfilled. Their equation shows that with a constant radon emanation rate, the atmospheric radon concentration varies inversely with the ventilation rate for any practical mine situation. That is, doubling the ventilation rate will decrease the atmospheric concentration by a factor of two.

Measurements of specific radon emanation rates were described by Thompkins and Cheng.[8] An open-ended gas chamber ($2' \times 2' \times 1'$) was bolted and sealed onto steel flanges set in exposed ore faces. Samples of air inside the chamber were taken for radon measurement and the emanation rate calculated. This procedure would be particularly useful for calculating ventilation requirements in mines where large ore bodies were being exploited.

PRINCIPLES GOVERNING THE BEHAVIOR OF RADON DAUGHTERS

The primary source of radon daughters in mine atmospheres is radon which is released into open areas as a pure gas, while the daughters are retained in the host rock. Immediately upon release of radon the transformation products start to form and accumulate in the air according to the laws of radioactive growth and decay. Knowledge of the behavior of radon daughters will be helpful in planning ventilation of working areas and in estimating the probable effectiveness of control measures such as filtration of ventilation air.

A concise and complete discussion of the behavior of radon daughters has been prepared by Evans.[9] This article presents the basic equations for calculating the atmospheric concentrations of each daughter at any time after the release of pure radon into open areas. Filtration of air to remove radon daughters will produce an analogous situation, so the same equations will apply. The article shows how to correct for "plate out" of daughters on surfaces and includes tables of growth factors and graphs which should be very helpful to mine ventilation engineers. Two particularly useful graphs are those shown in Figures 8 and 9.

Inspection of the curves in Figure 8 reveals the advantages gained by removing radon from working areas before the daughters have time to grow to equilibrium. As Evans points out, in 20 minutes only 30 percent of the equilibrium amounts of decay products will develop.

Figure 9 presents the early portion of 8 on an expanded scale. The curves in this figure would be particularly valuable for estimating the potential usefulness of filtration as a control measure. These points will be discussed further in the section on filtration.

The effect of ventilation on equilibrium ratios was mentioned earlier. Figure 6 displays theoretical curves showing the degree of equilibrium for each daughter versus ventilation rates. A graph can be constructed from these curves show-

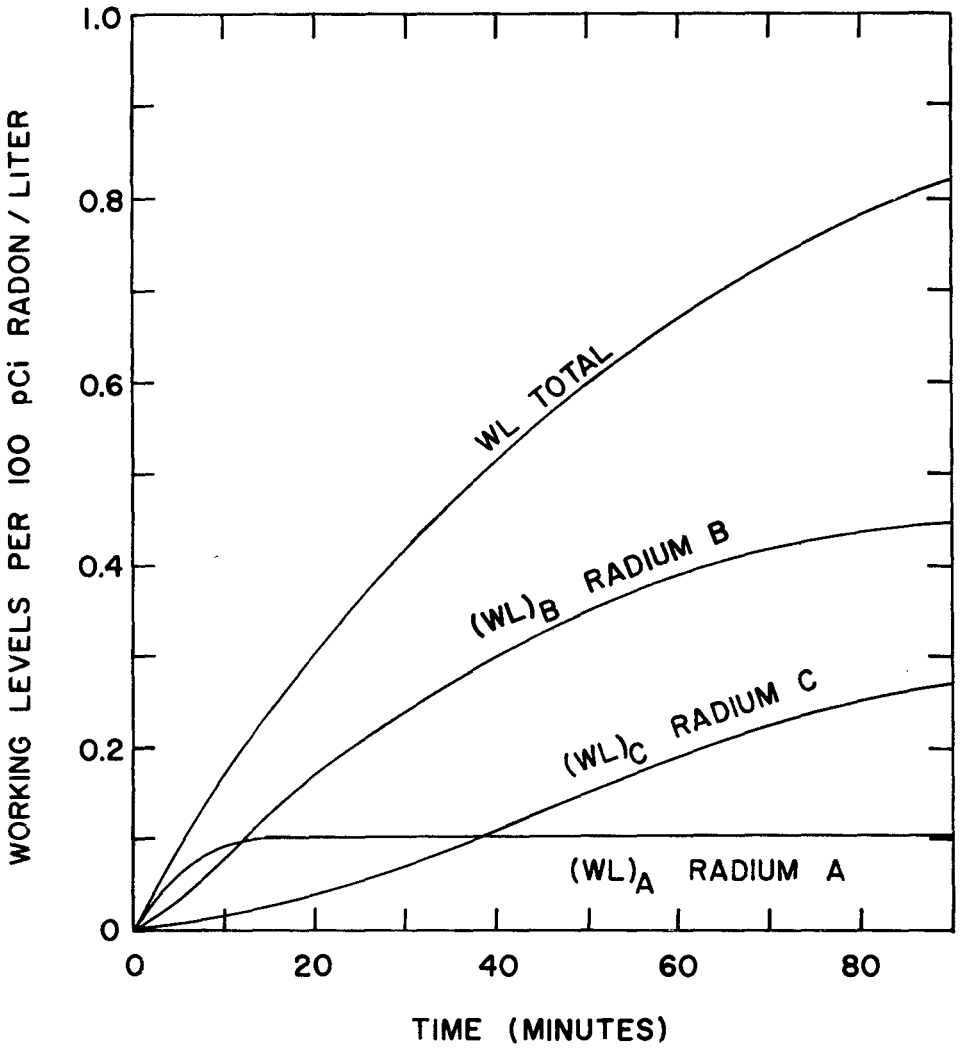

Figure 8: Growth of Working Levels in initially pure radon. (Evans[9])

ing the change in working levels with change in ventilation rates. Figure 10 presents this theoretical curve.

This graph again shows the marked effect of ventilation on the working level content of the air. As can be readily seen, it contains the same information as do Figures 8 and 9 but presented in different terms. Depending on the information available, one or the other form may be more useful to the ventilation officer for estimating amounts of air required for particular situations.

It should be kept in mind that these curves are theoretical. They are based on the assumptions that dilution ventilation is the only method of removal which is operating and that the ventilation air is uncontaminated. Neither one of these assumptions is correct in most mine situations, but use of these graphs will give first approximations of air requirements.

CONTROL OF RADON INFLUX

General Principles

The first principle in planning uranium mining operations is to limit release of radon into active areas. Once radon enters mine atmospheres the only method of removal now used is dilution ventilation, the costs of which may be much greater than the costs of restricting radon influx. The statement that there is no typical uranium mine is particularly applicable to the subject of radon emission. Table 13 for example, illus-

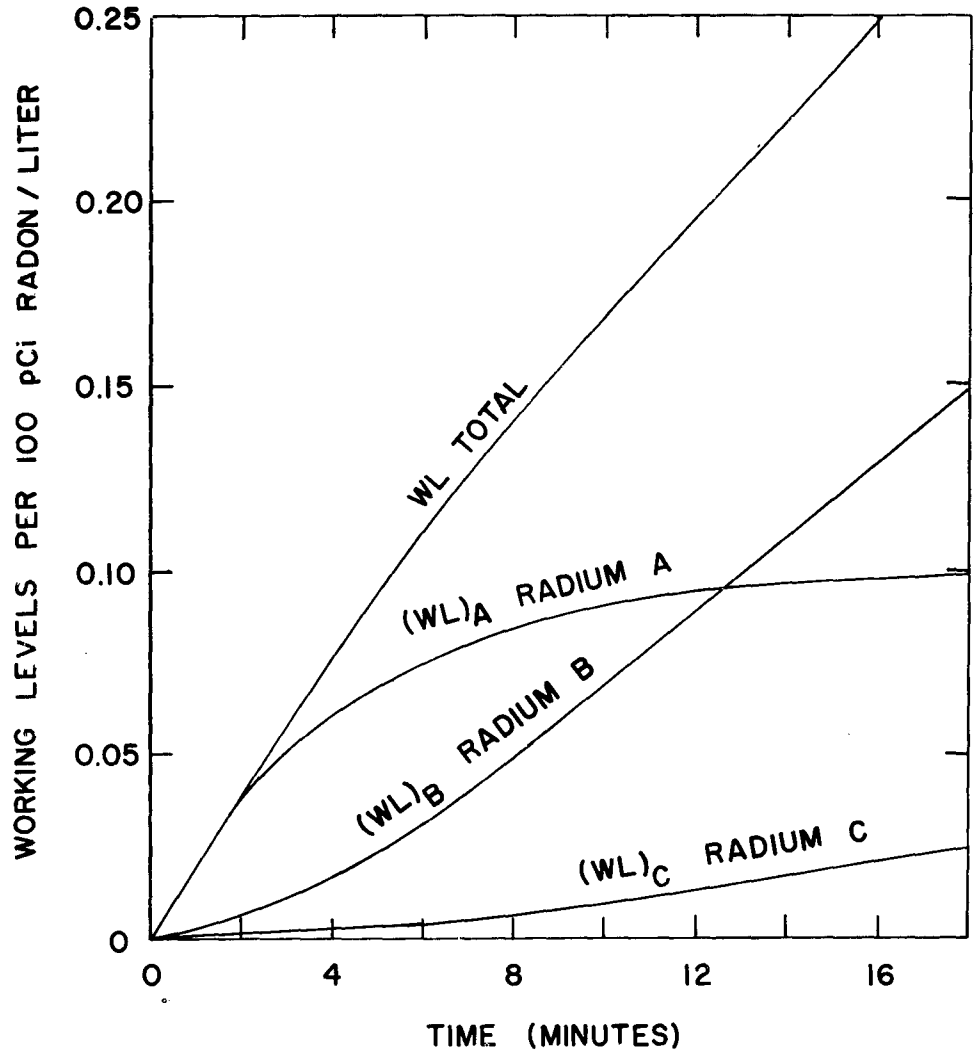

Figure 9: The growth of Working Levels in "young" air containing 100 pCi Rn/l., showing the early portion of Fig. 6 on an expanded scale. (Evans[9])

trates the wide variations in radon emanation rates which have been found.

Rock and Walker and Beranek discuss in detail the factors influencing release of radon into mine atmospheres. These are:

1. Area and grade of ore exposed.
2. Permeability of the host rock.
3. Porosity of the host rock.
4. Size and degree of aeration of broken ore.
5. Leakage of air from behind seals.
6. Mine pressure below atmospheric.

Thoughtful selection of methods of ore extraction and ore handling and proper layout of the mine facilitates control of radon contamination. These factors are determined in mine planning, and were mentioned earlier. Permeability and porosity of rock are beyond the operator's control, so in a working mine the only items about which much can be done are control of leakage of radon from behind seals and utilization of atmospheric pressure gradients wherever possible.

Utilization of atmospheric pressure gradients

Unworked and abandoned areas should be closed off to prevent leakage of radon into active areas. This can be difficult because radon can diffuse through materials such as concrete, and surprising amounts of contamination can leak

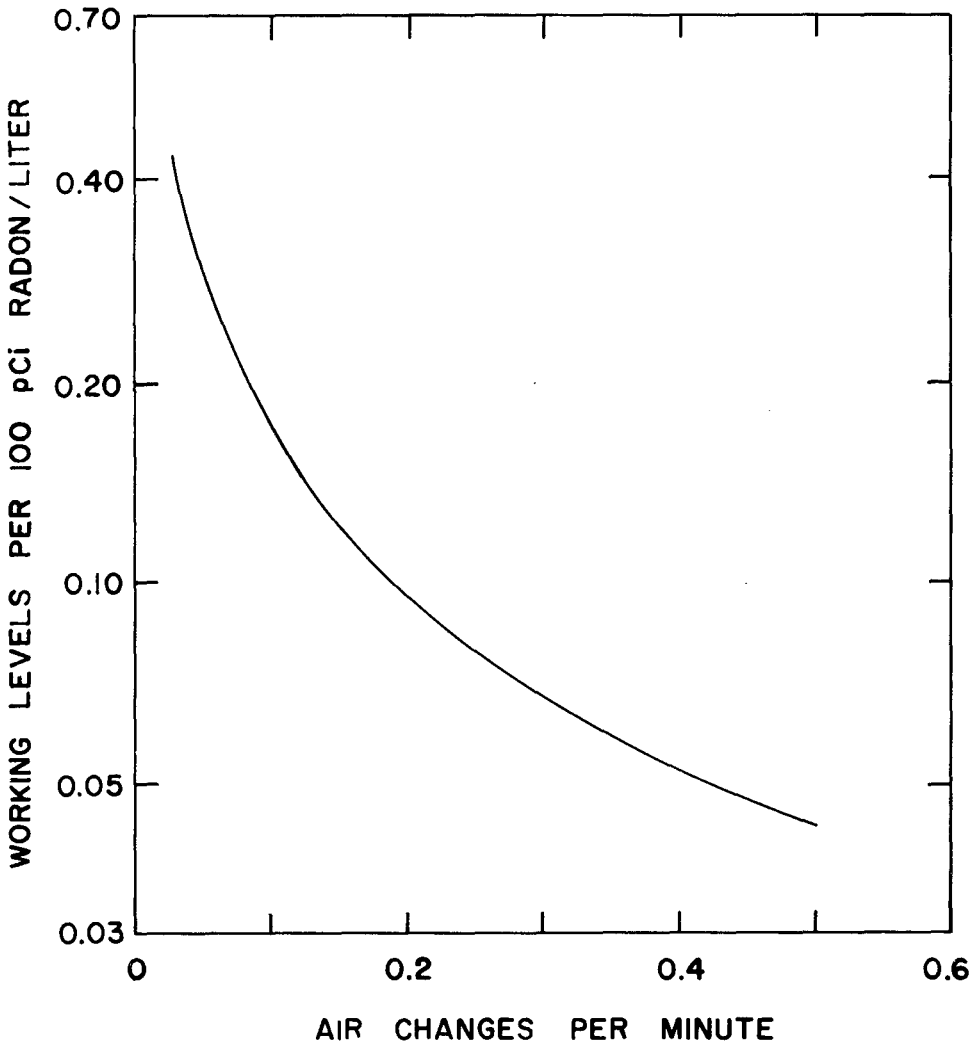

Figure 10: Working Level content of air per 100 pCi Rn/l vs. ventilation rate (Ventilation with uncontaminated air). (Fig. VI-4 PHS Publication No. 494)

through small openings in seals. Leakage is particularly severe if the pressure in the sealed stopes becomes higher than the pressure in the mine areas. That normal changes in atmospheric pressure can markedly influence radon concentrations was shown by Pohl-Ruhling and Pohl.[11] In the three mines which were studied the influx of interstitial radon per mm of mercury decrease in barometric pressure exceeded the amount of radon diffusing in from the rock surfaces. The authors state that natural ventilation far exceeded the artificial ventilation in these workings, and the atmospheric concentrations were quite high, ranging from 2,600 to 12,000 pCi/1. In mines with sufficient artificial ventilation to reduce radon daughter concentrations to 1 WL, the influence of changes in barometric pressure would not be as great. However, this effect could be an explanation for some of the unusual results which are found in mine surveys.

Overpressurizing of mine areas to reduce radon influx was studied by Schroeder, Evans and Kraner.[14] In the mine areas which they studied an overpressure of 1 cm of mercury (about 1.5 percent of atmospheric pressure) decreased the radon flux 5- to 20-fold as compared to that occurring during normal dilution ventilation. The effectiveness of overpressurization depends on pressure, rock permeability and availability of a pressure "sink" toward which interstitial air can

flow. These investigators suggested putting mined out areas and drill holes under negative pressure. Interestingly, a procedure of draining methane from coal mines by similar methods has been used in Belgium. Large scale tests of overpressurization systems have been conducted but no reports have been published. The concept is intriguing, but considerable experimental work is required to define its utility in control of radon influx.

Control of Radon Influx by Use of Sealants

Reduction of the influx of radon into working areas by application of materials which are relatively impervious to radon to stoppings or to rock surfaces is an attractive procedure for control of atmospheric contamination. The difficulties are to find materials which are impervious to radon and to develop methods of application which will insure that the materials will adhere to surfaces in mines and be economically practical. Unpublished studies by Craft at the United States Public Health Service Salt Lake City Field Station showed that polyurethane foams will inhibit diffusion of radon from rock, and this material is used in some mines to seal cracks in bulkheads. The most extensive study of diffusion of radon through various materials has been done by Gibbs[17] at the United States Bureau of Mines Station in Salt Lake City. Table 15 presents some of the findings of this as yet unpublished work.

The diffusion coefficients were measured by sealing disks of the test material to a chamber containing a radon source and taking radon samples at intervals from a container sealed to the other side of the disk. The results show the relative impermeability of latex, urethane and epoxy paints to radon. Other tests by Gibbs of 1/16 inch butyl rubber and 1/32 inch mylar sheets showed zero permeability in two hours. No tests of these materials in uranium mines have been reported. Mylar sheets have previously been found to be impervious to radon.

Two reports of use of polyurethane foams and mylar curtains in gold mines have been published. Stafford[12] described a method for erecting polyurethane brattices which was developed at the President Brand mine in South Africa. The procedure is:

1. Install 8 oz. hessian, scribe to footwall and hanging wall and staple to packs.
2. Cover hessian with 1 inch mesh chicken wire, scribe to footwall and hanging wall and staple to packs over hessian.
3. Extend four strands of 8 gauge wire around packs and over chicken wire from pack to pack. Pull wires tight, staple around pack and wire to chicken mesh.

Table 15. DIFFUSION OF RADON THROUGH VARIOUS MATERIALS

Material	Percent radon diffused[1]	Diffusion coefficient[2] $cm^3/cm^2/min$
1. 1 in. clear pine	6.4	1.2×10^{-2}
2. 1 in. clear pine (urethane paint)	0.6	1.1×10^{-4}
3. 0.5 in. plaster board	89.8	4.4×10^{-1}
4. 0.5 in. plaster board (latex paint)	0.8	1.5×10^{-3}
5. 0.5 in. plaster board (epoxy paint)	0	$<1.6 \times 10^{-6}$
6. 0.25 in. Masonite	49.8	1.3×10^{-1}
7. 0.25 in. Masonite (epoxy paint)	0	$<1.6 \times 10^{-6}$

[1]Percent diffused as measured by the two hour sample.

$$\frac{\text{Conc. Rn. in diffusion container}}{\text{Conc. Rn. in source chamber}} \times 100$$

[2]Diffusion coefficient or transfer rate λ calculated from the formula $-\frac{1n\ C_1\ C_2}{C_1} = \lambda t\ \frac{A}{V}$ where:

C_1 = conc. in radon source bex
C_2 = conc. in radon collection bottle
t = 120 min.
A = area of test piece in cm^2
V = volume of radon collection bottle (3 liters)
$\lambda = cm^3/cm^2/min$
(After Gibbs[17])

4. Spray with polyurethane.

Brattices thus made will resist concussion and should be essentially impervious to radon. *Caution*: All unreacted urethane foams contain isocyanates. Proper respiratory protection *must* be worn by all personnel engaged in spraying.

Bell[13] described a procedure for hanging polyvinyl chloride (mylar) curtains which is used in South Africa. The sheets are threaded on wire which is hooked to packs at each end of the area to be curtained. Dust is hosed off the hanging wall, a thin layer of epoxymastic is spread in a 2 inch wide strip along the hanging wall and the curtain and wires pressed into it. The curtains are held in place by a headboard until the epoxymastic has set. The bottom of the curtain is then weighted down with rocks and fines. Some slack should be left in the curtain to prevent rupture by concussion. *Caution*: Epoxy cements cause dermatitis. *Rubber gloves must be used.*

Control of Radon by Adsorption

Obviously an effective method of controlling radon daughter concentrations would be to remove radon from the air stream. The feasibility of using activated carbon and molecular sieves to adsorb radon in mine atmospheres was studied by Coleman, et al[15], Schroder, et al[16] and Fusamura, et al[17]. All of these investigations concluded that the quantities of carbon required were too large. Thomas[18] has reported laboratory investigations of an adsorption technique employing a multiple bed-temperature cycling process. Thomas' abstract states: "A brief study was made of the feasibility of using activated carbon to remove radon in uranium mines with use of a multiple bed-temperature cycling process. Air containing radon is passed through a carbon bed at ambient temperature until the bed is considered exhausted. The bed is then heated to about 120°C and the radon desorbed, using a much smaller volume of air than was used during adsorption. The desorbed radon, after cooling, is passed into a second bed. Since the capacity of the carbon depends primarily on the volume of air passed into it rather than the quantity of radon adsorbed, the second bed will adsorb much more radon than the first. Multiple stages of this process are possible. It was extrapolated from experiments that about 10 liters per minute or more of air could be purified continuously of radon per liter of carbon."

Control of Radon by Chemical Removal

Stein[19] has investigated the ability of a number of solid complexes of halogen fluorides and metal fluorides to remove radon from air. In laboratory tests such compounds as ClF_2SbF_6, BrF_2SbF_6 and $BrF_4Sb_2F_{11}$ were very effective in removing radon and daughters from air. Field tests to evaluate the potential utility of this approach to controlling radon would be desirable.

CONTROL OF RADON DAUGHTERS BY VENTILATION

After radon has entered mine atmospheres, the principal procedure for controlling atmospheric concentrations of radon daughters is dilution ventilation. The general principles of mine ventilation are well-known and are applicable to uranium mines. However, special considerations must be kept in mind. These items are treated in references 1 and 2, and will only be mentioned here. They are:

1. Maintaining efficiency of air distribution through all connected mine workings.
2. Use of directional ventilation to direct contaminated air away from the men.
3. Avoiding recirculation of air.
4. Continued attention to eliminating leaks from sealed areas.

Attention to these factors is more important in controlling contamination by radon daughters than is the case with the dusts and gases which are usually encountered. Because of the rapid ingrowth of radon daughters, air should be kept moving through the entire volume of working areas to maintain the residence time of air as low as possible. Small leaks in seals or doors can release highly contaminated air into air streams, in many cases rendering them useless for ventilation purposes. Surveys of six uranium mines made in 1967 by the United States Bureau of Mines reported by Rock[20] identified the causes of high atmospheric concentrations of radon daughters. Table 16 summarizes the findings of these surveys.

Following the radiation-ventilation surveys, changes in mining and ventilation practices were made in five mines. (In the other, the radiation survey preceded the radiation-ventilation survey.) Figures 11 and 12 display graphically the findings of these surveys in two mines.

Table 17 compares the man-exposure data obtained in these two series of surveys.

Table 16. SUMMARY OF MAJOR CAUSES OF HIGH RADON DAUGHTER EXPOSURE LEVELS

Major causes	Relative cause importance						
	At individual mines[1]						Overall[2]
	1	2	3	4	5	6	
Unnecessary acceptance of contamination inflow ..	2	6	6	5	1	6	26
Poorly designed auxiliary ventilation systems (recirculation or improper delivery at the face)	5	4	4	4	4	4	25
Insufficient ventilation quantity (judged on the basis of efficient distribution and utilization of available air)	4	3	3	2	6	5	23
Series ventilation between major mining sections	3	5	2	6	2	3	21
Lack of directional control over available air	6	1	5	1	5	1	19
Main operating openings in return air	1	2	1	3	3	2	12

[1]Cause importance at each mine is indicated by the decreasing range 6-1.
[2]Cause importance for all mines is indicated by the decreasing range 26-12.
From Bureau of Mines, Dept. of Interior, I.C. 8413[16]

The data in Table 16 shows the effects of better use of available ventilation air. They also indicate that it was relatively easy to reduce atmospheric concentrations of radon daughters greater than 3 WL to lower ranges, but that it was more difficult to reduce exposures in the two lower ranges. The report concludes that the broadest problems in these mines was lack of mine planning for radon daughter control. These mines were all in mature stages of development with much of the planning having been done before 1960 before the necessity for control was widely recognized. It is probable that they were representative of older United States uranium mines. Future mines will be planned with radiation control in mind, so many of the problems encountered in older operations will be obviated.

EXAMPLES OF RADON DAUGHTER CONTROL PROGRAMS

The topics of ventilation of uranium mines, both primary and secondary systems, are so well covered by Rock and Walker and by Beranek that there is no necessity for repeating the discussion here. Instead specific examples representing widely different types of mines will be treated in detail.

Ventilation Practices at Denison Mines, Ltd.

This section is a condensation of the material presented in a report by Frame.[5] The Denison mine is representative of high production mines working well-defined ore bodies extending over a large area. The ore zone consists of five distinct uraniferous zones, separated by practically barren quartzite. The proven and probable reserves extend over about 3200 acres. The present production is at a reduced rate of 5500 tons of ore per day. The mining method is room and pillar with in-ore development. A well-trained ventilation staff reports directly to management, and underground supervisors are responsible for both ventilation and safety. The ventilation system delivers slightly more than 500,000 cfm underground through two shafts. In the winter the air is heated by burners with a capacity of 30,000,000 BTU's per hour. The fresh air is delivered at high velocities and expelled through worked-out areas which are sealed off from the operating sections. The present mining and ventilation systems are the result of extensive alterations and changes in mining methods and ventilation circuits. Ore is now extracted from a single block at a time to minimize the number of active panels. The basic change in the ventilation system was reduction of delivery and return routes. Air is forced down the fresh air shafts and removed by an exhaust fan. This system assures that mining areas are under positive pressure. Stoppings are under high pressure on the fresh air side and under low or negative pressure on the exhaust side. Uncontrollable leakage thus goes to exhaust. To the date of the report $2,701,000 had been spent on the changes and remaining work would require $469,000 more.

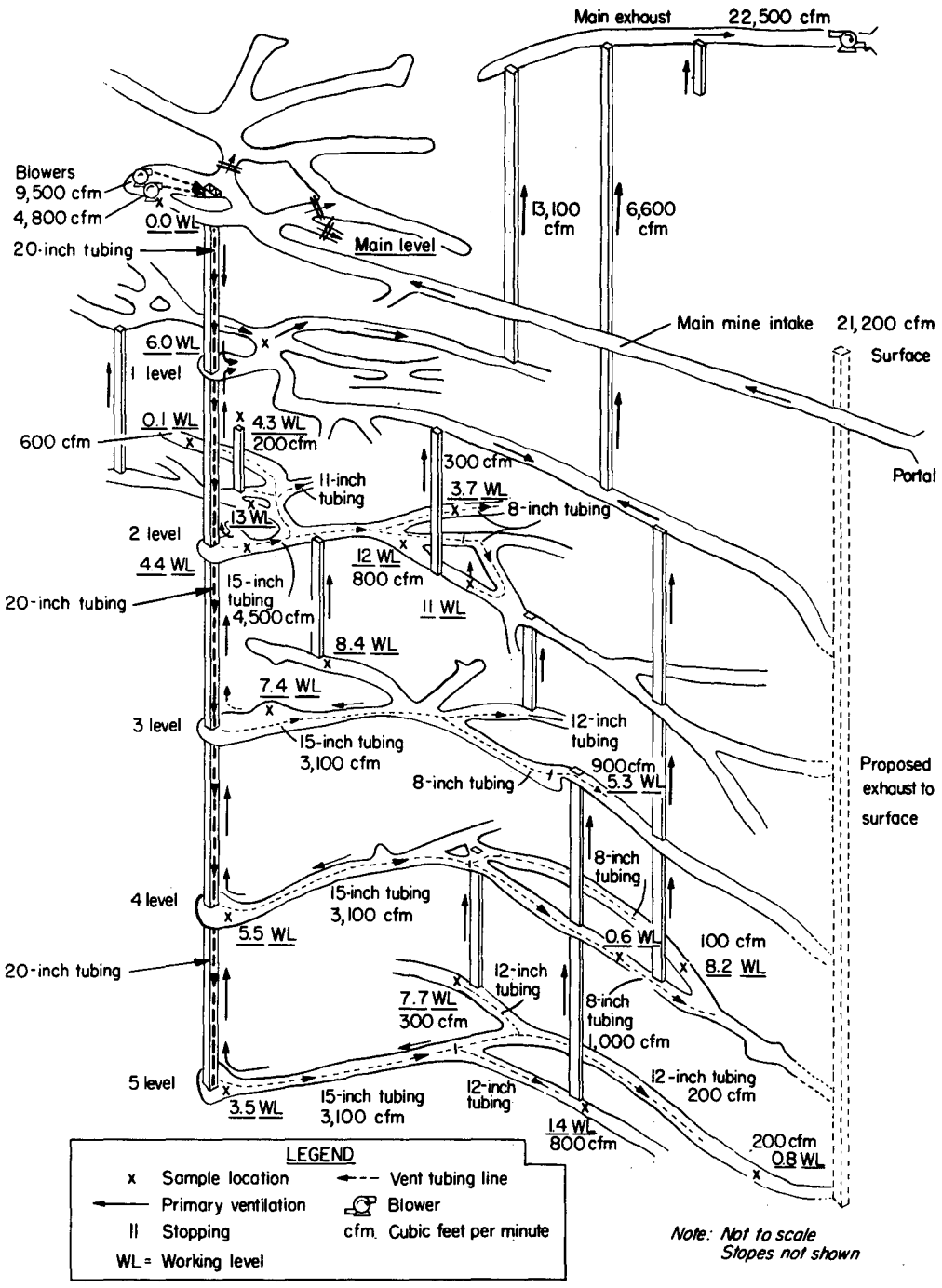

Figure 11: Isometric sketch showing radiation-ventilation relationships at Mine 5. (Rock[15])

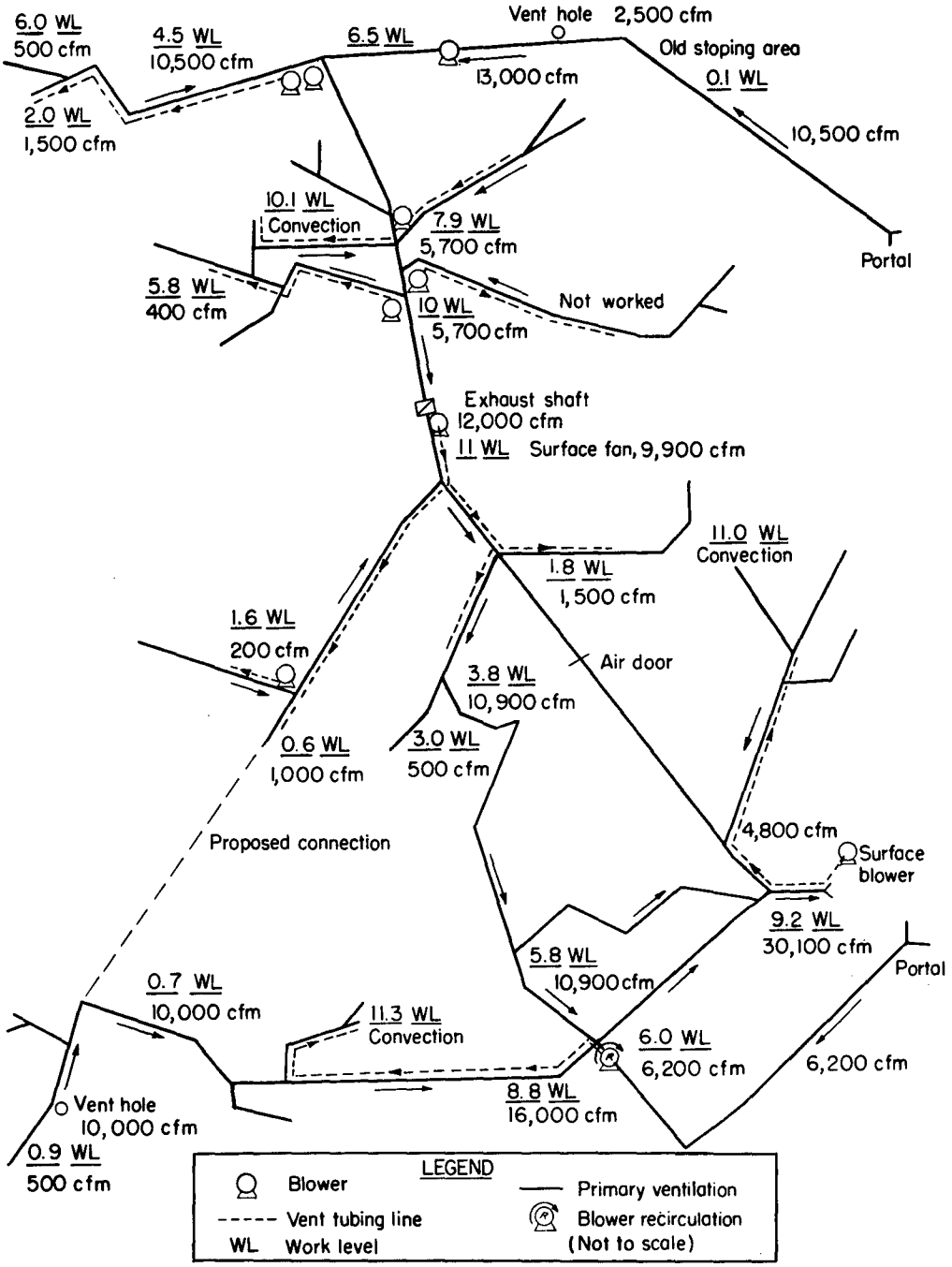

Figure 12: Plan line diagram showing radiation-ventilation relationships at Mine 6. (Rock[15])

Table 17. COMPARISON OF PERCENTAGES OF MEN IN VARIOUS FULL-SHIFT EXPOSURE RANGES DURING RADIATION-VENTILATION STUDIES AND RADIATION SURVEYS[1]

Study and survey	Men exposed to various working level ranges, percent					
	0-0.3 WL	0.4-1.0 WL	1.1-3.0 WL	3.1-5.0 WL	5.1-10.0 WL	>10 WL
MINE 1						
Radiation-ventilation study	74	17	9	—	—	—
Cumulative, percent	74	91	100	—	—	—
Radiation survey	29	60	9	2	—	—
Cumulative, percent	29	89	98	100	—	—
MINE 2						
Radiation-ventilation study	2	11	54	30	3	—
Cumulative, percent	2	13	67	97	100	—
Radiation survey	22	64	14	—	—	—
Cumulative, percent	22	86	100	—	—	—
MINE 3						
Radiation-ventilation study	56	11	6	6	16	5
Cumulative, percent	56	67	73	79	95	100
Radiation survey	43	46	8	0	3	—
Cumulative, percent	43	89	97	97	100	—
MINE 4[2]						
Radiation survey	0	0	0	18	82	—
Cumulative, percent	0	0	0	18	100	—
Radiation-ventilation study	0	42	58	—	—	—
Cumulative, percent	0	42	100	—	—	—
MINE 5						
Radiation-ventilation study	21	15	27	9	21	7
Cumulative, percent	21	36	63	72	93	100
Radiation survey	48	32	20	—	—	—
Cumulative, percent	48	80	100	—	—	—
MINE 6						
Radiation-ventilation study	0	4	21	23	52	0
Cumulative, percent	0	4	25	48	100	—
Radiation survey	0	4	89	0	7	0
Cumulative, percent	0	4	93	93	100	—

[1]Slightly higher exposure levels obtained during radiation surveys are believed to represent a fluctuation within normal transient conditions.

[2]Radiation survey made prior to radiation-ventilation study.

From Bureau of Mines, Dept. of Interior, I.C. 8413[15]

The effects of these changes on radiation levels are listed in Table 18.

The report points out that 2.5 years and several million dollars were required to lower the mean mine radon daughter level from 1.08 WL to 0.64 WL.

Several features of this operation are of particular interest. The radon emanation rate from the rock is only 0.5 pCi/sec/ft^2 (about 5 pCi/sec/m^2). This is equivalent to the lowest category shown in Table 13, and is about one percent of the values indicated by Schroeder in some United States mines. This low emanation rate meant that air courses could be established in ore and still provide usable air at working headings. The air from Number 1 Shaft was de-

Table 18. MEDIAN WORKING LEVELS, DENISON MINE

Working place category	1967	Period Jan. to Sept. 1968	Oct. to Dec. 1968	Jan. to March 1969
Heading	1.02	1.09	0.90	0.61
Raises	1.42	1.32	0.68	0.69
Slopes	1.29	1.27	0.89	0.72
Travelways and airways	0.76	0.93	0.63	0.49
Miscellaneous locations	0.74	1.07	0.79	0.53
Total for mine	1.08	1.16	0.79	0.64

From Frame, Canadian Mining J.[5]

livered over 3000 feet at less than 0.1 WL, while that from Number 2 Shaft arrived at less than 0.2 WL after traveling 6000 feet. The report gives examples showing how the graphs in Figures 8 and 9 can be used to calculate ventilation requirements for headings. Additional information required are radon emanation rates which must be determined for the specific situation under study. At Denison, only a small part of the radon contamination results from diffusion from rock surfaces. The major portions are contributed by leakage from worked-out areas, broken ore piles, and recirculation. The report states that it is hoped with rigid control procedures and more training of personnel, the mine average can be reduced to about 0.5 WL.

Respirators are used for those areas which exceed at least temporarily the acceptable levels for radon daughters or dust. A low-resistance dust respirator is used for protection against dust and diesel fumes. This type also removes 50 percent of the radon daughters. High efficiency air filtering respirators are used in areas where the radon daughter concentrations range from 1 WL to 4 WL. An overall efficiency of 75 percent is assumed to allow for face leakage. In areas when the concentrations range from 4 WL to 20 WL, battery-powered air supplied filtering respirators are required. They are used exclusively by leaching operators. On those rare occasions where the concentrations exceed 20 WL, self-contained breathing apparatus is used.

The work at Denison has shown that it is possible to plan mining and ventilation operations to attain control of radon daughter concentrations. To accomplish this requires utilizing theoretical information, practical experience and continued attention to details of air direction, maintenance of stoppings and air doors and use of personal protective devices where required.

Ventilation Practices in the Uravan Mineral Belt

The Uravan Mineral Belt in Colorado is one of the oldest uranium mining districts in the United States. These mines are characterized by the irregular and intermittent nature of the ore bodies which occur in pods and lenses containing from a few hundred to a few thousand tons of ore each. Some of the ground is fractured and faulted which adds to the problems. The nature of the deposits means that their size and extent cannot be predicted accurately, which makes advance mine planning and ventilation planning difficult. Figure 12 illustrates the complexity of underground workings in these operations.

The Mining and Metals Division of Union Carbide Corporation operates many mines in the Uravan Mineral Belt, and the problems which they have encountered are characteristics of those which occur in a great many small and medium-sized uranium mines. The radon daughter control program which has been developed by Union Carbide was described by Swindle[21] and the material in this section is largely taken from that report.

Advance planning of a new ventilation system must be based entirely on past experience with similar ore bodies. The factors that affect radon emanation rates are grade and size of ore bodies, degree of oxidation of the ore and fracturing. Radon emanation rates from oxidized ores are considerably higher than from unoxidized ores, with high grade carnotite ore having the highest emanation rate. Fractures facilitate diffusion of radon and open fractures provide stagnant areas where radon can accumulate and reside long enough for ingrowth of the daughters. All ventilation air in a mine does not have the same residence time, except for a few small mines. The complexity of workings and the interconnections between workings result in some of the air moving rapidly through the mine while the rest will remain stagnant for varying time periods before it returns to the main air course. As a consequence of all these variations neither the dilution-growth curve (Figure 8) nor the dilution-ventilation curve can be used to predict ventila-

tion requirements accurately. Educated estimates based on experience have been found to be the best guide. Uncertainties in estimates of additional ventilation requirements can be reduced by measuring atmospheric concentrations of both radon and radon daughters to define conditions as accurately as possible.

Isolation of inactive areas is practiced wherever possible, but in many cases this cannot be done because openings are too large and too numerous. Additionally, it is often difficult to determine how long an inactive area will remain so. For example, discovery of new ore bodies may require use of "inactive" areas for exploitation purposes.

The best material for sealing brattices is urethane foam. However, it has been found that nearby blasting can break the foam and in some instances that it is difficult to form a permanent seal with the rock at the edges of the brattice. It has been possible to exhaust a small quantity of air through a vent hole in an inactive area, thus assuring that leakage of contamination will be away from active areas.

Considerable experimental work has been done with mechanical filters to remove radon daughters, thus permitting further use of ventilation air before it is rejected to the return air course. The filters used were a sock type, with a filter media consisting of a 0.25 inch sub-micron fiberglass batt supported on dacron netting. A two-inch thick glass fiber batt pre-filter was used to extend the life of the filters. Used in a wet mine these filters showed about 75 percent efficiency for removal of radon daughters. Moisture caused deterioration of the filters in five and one-half months. Socks came apart and all frames became unglued. It might be possible to develop more rugged filters, but increasing use of diesel equipment makes use of mechanical filters less attractive, as diesel smoke would plug the material quite rapidly. Air cleaning could be a valuable aid to control and other types of devices are being considered.

EFFECT OF CONTROL WORK ON EXPOSURES OF MINERS

The first extensive series of uranium surveys were made in 1952, when measurements of atmospheric concentrations of radon and radon daughters were made in all uranium mines (157) which could be located. Table 19 lists the findings of those surveys.

Table 19. DISTRIBUTION OF MINES AND MINERS BY RADON DAUGHTER CONCENTRATIONS. 1952

Radon daughters expressed in multiple of working level (WL)	Mines		Miners	
	Number	(%)	Number	(%)
0.49	35	22.3	116	15.8
0.5-2.49	27	17.2	117	16.0
2.5-9.9	25	15.9	171	23.3
>10	70	44.6	329	44.9
Total	157	100.0	733	100.0

After Table 2-3 PHS Publication No. 494, Pg. 4

At that time, uranium mines were ventilated primarily to control silica dust and mine gases. Some mechanical ventilation was used, but natural ventilation was the principal method of control. The mines were shallow, relatively small and there was often little difference in elevation between the collars of upcast and downcast shafts. As a consequence, air movement was limited and erratic. Examination of Table 18 shows that 55 percent of the men were exposed to atmospheric concentrations of radon daughters in excess of 10 WL and that only 32 percent were exposed to less than 3 WL. In succeeding years more ventilation was introduced as the industry and regulatory agencies became more aware of the hazards produced by exposure to radon daughters. It is not possible to assemble industry-wide data on an annual basis for the period 1953-1961 as comprehensive surveys similar to those done in 1952 were not undertaken. In 1961 and 1962 the United States Bureau of Mines measured radon daughter concentrations on two occasions in each of the larger uranium mines and in most of the smaller ones. Samples were taken in all occupied mine areas and time studies made to obtain information from which to estimate time-weighted full shift exposures. Tables 20 and 21 show the findings of these two campaigns.

The data in these tables are not directly comparable to those in 19 as exposures in that table were estimated on a mine average rather than a weighted-average basis. However, some inferences can be drawn concerning the changes in atmospheric concentrations of radon daughters in the 10 years following 1952. Only five percent of the miners were exposed to concentrations exceeding 10 WL in 1962, as compared with 55 percent in 1952, while the number exposed to

less than 3 WL had increased from 32 to 74 percent. Efforts to improve controls were continued after 1963, primarily by state agencies and the larger mining companies. In 1967 the United States Bureau of Mines resumed environmental surveys. Tables 22, 23 and 24 present the findings of surveys during selected periods of 1967, 1968 and 1969.

Comparison of the data obtained in 1969 with that from the 1962 surveys shows that a negligible percentage of miners were exposed to more than 10 WL in 1969. The number exposed to less than 3 WL had increased to 97.8 percent, and 80.5 percent were exposed to less than 1 WL. These changes indicate the effectiveness of work on control which took place between 1962 and 1969.

It is hazardous to draw too many conclusions from the information obtained in these surveys but some trends are apparent. Between 1962 and 1967 there was a general shift toward lower exposures with an almost complete elimination of exposures to over 10 WL. Between 1967 and 1968 there was again a downward shift which

Table 20. ESTIMATED FULL-SHIFT EXPOSURE RATES TO RADON DAUGHTERS. FIRST INSPECTION 1961-1962 (139 mines)

Average exposure rates (working level)	Number of men exposed	Percent men exposed	Cumulative percent
0.-1.0	1,007	45	45
1.1-3.0	627	29	74
3.1-5.0	312	14	88
5.1-10	163	7	95
>10	104	5	100

After Bureau of Mines, Dept. of Interior[23]

Table 21. ESTIMATED FULL-SHIFT EXPOSURE RATES TO RADON DAUGHTERS. SECOND INSPECTION 1961-1962 (119 mines)

Average exposure rates (working level)	Number of men exposed	Percent men exposed	Cumulative percent
0.-1.0	978	44	44
1.1-3.0	675	30	74
3.1-5.0	254	11	85
5.1-10.0	251	11	96
>10	84	4	100

After Bureau of Mines, Dept. of Interior[23]

Table 22. ESTIMATED FULL-SHIFT EXPOSURE RATES TO RADON DAUGHTERS. APRIL 1-JUNE 30, 1967 (119 mines)

Average exposure rates (working level)	Number of men exposed	Percent men exposed	Cumulative percent
0-0.03	384	30.1	30.1
0.4-1.0	370	29.0	59.1
1.1-3.0	313	24.5	83.6
3.1-5.0	101	7.9	91.5
5.1-10.0	89	7.0	98.5
>10	19	1.5	100.0
Total	1,276	100.0	

After Bureau of Mines, Dept. of Interior[23]

Table 23. ESTIMATED FULL-SHIFT EXPOSURE RATES TO RADON DAUGHTERS. APRIL 1-JUNE 30, 1968 (63 mines)

Average exposure rates (working level)	Number of men exposed	Percent men exposed	Cumulative percent
0-0.3	358	47.3	47.3
0.4-1.0	290	38.3	85.6
1.1-3.0	81	10.7	96.3
3.1-5.0	15	2.0	98.3
5.1-10.0	4	0.5	98.8
>10	9	1.2	100.0
Total	757	100.0	

After Bureau of Mines, Dept. of Interior[23]

Table 24. ESTIMATED FULL-SHIFT EXPOSURE RATES TO RADON DAUGHTERS. JULY 1-DECEMBER 31, 1969 (79 mines)

Average exposure rates (working level)	Number of men exposed	Percent men exposed	Cumulative percent
0-0.3	570	44.5	44.5
0.4-1.0	461	36.0	80.5
1.1-3.0	222	17.3	97.8
3.1-5.0	20	1.5	99.3
5.1-10.0	6	0.5	99.8
>10	2	0.2	100.0
Total	1,281	100.0	

After Bureau of Mines, Dept. of Interior[24]

was probably real. In the 1968-69 period, the changes were minor, but still tended downward. The first year in which the necessity for control of radon daughters was generally recognized by regulatory agencies and the mining industry was 1961. The survey results reflect improvements in conditions between 1962 and 1967. In 1967 extensive efforts to improve controls were started, criteria for ventilation were made more stringent, and studies were made of methods of using ventilation more effectively. These efforts have continued, and have succeeded in lowering atmospheric concentrations somewhat. However, the data seem to show that ventilation alone will not reduce atmospheric concentrations of radon daughters to much lower levels than were prevalent in 1969. At the relatively low levels of atmospheric contamination which existed in 1969 it is difficult to evaluate conditions, but it appears that efforts to improve quality of ventilation air would be more productive than attempts to increase the quantity of dilution ventilation. Studies of methods of reducing radon emission into working areas, more effective and more lasting means of closing off inactive areas, more acceptable respirators, and means of removing radon from mine air might well result in further reductions in atmospheric contamination.

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EVALUATION OF INDIVIDUAL EXPOSURES

INTRODUCTION

The primary means for limiting exposures of miners to radon daughters is control of the atmospheric concentrations of these elements. If the atmospheric concentrations never exceed a certain value, such as 1 WL, obviously a miner will not accumulate more than 1 WLM per working month. In practice he will accumulate radiation dosage at a considerably lower rate, because the average atmospheric concentration in a mine must always be lower than the maximum. However, in the present state of technology, it is not possible to insure that no working areas in a mine will be higher than a stated level unless the level is set irrationally high. Therefore, procedures for evaluating individual cumulative exposures are required to identify those men who have exceeded, or who may exceed, the recommended annual cumulative radiation dose. Once they have been identified, corrective measures, such as assignment to known low-exposure areas, can be taken. It must be recognized that in the present state of the art, evaluations of individual exposures are only estimates which may be far from accurate. If the errors are random, over- or under-estimates of exposure during each limited period, such as three months or a year, will not significantly affect the estimates of total exposure for a working life-time. It would be desirable if it were possible to limit the error in total cumulative exposures to plus or minus 25 percent. In that case, an estimated cumulative exposure of 360 WLM would mean that the individual's exposure was between 270 and 450 WLM. Errors of 50 percent in annual exposure estimates would seem to be acceptable. This degree of accuracy probably cannot be attained with procedures presently available. Several approaches to the problem of evaluating individual exposures will be described in this section.

TIME-WEIGHTED, FULL-SHIFT EXPOSURES

A procedure for estimating time-weighted, full-shift exposures was developed by Bates and Rock[1] and is used by the United States Bureau of Mines in their surveys. It consists of taking atmospheric samples in all working areas and estimating the time spent in each area by individual miners. Each sample is weighted for the portion of the day spent in that area and the individual exposures calculated. This procedure is the same as the one generally used by industrial hygienists for toxic materials and so has the advantage of being familiar.

AMERICAN NATIONAL STANDARD PROCEDURE

The procedure recommended in American National Standard N13:1-1970[2] is a more elaborate method for developing cumulative exposure records, and is the one commonly used by uranium mine operators in the United States. The applicable section of the Standard recommends:

"7.2 *Exposure Samples.* These samples are collected for use in conjunction with time records for calculating cumulative exposure of personnel. Normally in a given mine area, the atmospheric concentrations of radon daughters will not vary widely unless the ventilation conditions or the quality of the ore changes. Under such conditions relatively few air samples are necessary to make projected cumulative exposures for individual workers. Cumulative exposure shall be determined by a procedure that will yield an annual mean having a standard error no greater than 50 percent at the 95 percent confidence level. An acceptable method consists of calculating cumulative exposure monthly as defined in Section 2 based on: (a) Monthly measurement of the concentration of radon daughters in each active area of the mine by the sampling procedure given in Appendix 3. Samples collected for this purpose shall be random with time. (b)

Monthly summation of weekly time records showing the time spent by each employee in each underground work area.*

Appendix D of the Standard gives examples of record forms and instructions for compiling the required data.

RANDOM SAMPLING MAN-MONITORING PROCEDURES

The American National Standard procedure requires extensive calculations and record-keeping which can become burdensome. A simplified method described by Breslin[3] eliminates time-occupancy records and thus significantly reduces the volume and complexity of calculations and records. Breslin proposed that periodic samples be taken for each *miner* rather than for each *work area*. The samples should be random with time, in which case the miner's exposures for any given period would be the arithmetic mean of all samples taken for him during the period. The number of samples required to yield an acceptably accurate estimate depends on the variation in radon daughter concentrations to which the miners are exposed during any long period.

Data on atmospheric concentrations of radon daughters collected in 19 uranium mines over a six month period were analyzed by Breslin. The frequency distributions of atmospheric concentrations in each mine were determined and the standard deviations were calculated. Figure 13 shows the results of these analyses.

Examination of Figure 13 shows that in about 50 percent of the mines the standard deviation of the atmospheric concentrations of radon daughters was less than 0.8 WL.

Using this information on the variance in atmospheric concentrations in mines, Breslin calculated the errors in estimates of annual exposures for individual miners for weekly and bi-weekly sampling routines. The resulting graphs are shown in Figure 14.

In the mine showing the widest variations in concentrations the errors would be 40 percent and 28 percent for bi-weekly and weekly sampling. In half the mines the errors would be 26 percent and 19 percent or less.

The principle of this method was tested in two uranium mines. In each mine nine men were monitored by hourly WL measurements and the time spent in each area was recorded. Exposure estimates were prepared from these data. During the same period the WL at each miner's position was measured twice weekly on random days at random times. Figure 15 shows the comparison of results obtained by the two methods.

The points are close to the 45 degree line, indicating good correlation between the two procedures.

MINE AVERAGE EXPOSURES

The mine average atmospheric concentration of radon daughters for estimating the exposures of all the men working in that mine was employed by the United States Public Health Service in its epidemiological study. This is inherently a less precise procedure than those described previously, but is much quicker, and when few samples are available it may be the only possible procedure. Comparison of exposure estimates calculated by the weighted average procedure and the mine average showed that the mine average method produced higher estimates. Usually the ratios of the two values were 1.5 or less, but they could be as high as 4.0 in mines where the atmospheric concentration of radon daughters was less than 1 WL.

PERSONAL DOSIMETERS

Compiling data from which exposure estimates can be calculated is time-consuming and the results are always open to question. Therefore, the prospect of developing personal dosimeters which would record the alpha radiation to which miners are exposed is appealing. An ideal dosimeter could be worn by a miner for extended periods and would reduce the man-hours required to calculate exposure estimates. The estimates also might be more accurate than those made by other methods.

Several types of dosimeters based on different principles have been developed. These include: two types utilize thermoluminescent dosimetry; another relies on the alpha track etch phenomenon; still another uses alpha track emulsions. McCurdy et al[4] reported the results of an extensive development and evaluation program involv-

*NOTE: In arriving at this system a statistical evaluation of 4500 air samples from 179 locations in 22 mines, both large and small, was conducted. Additionally, time records from several mines covering six months were reviewed and mine record-keeping practices were discussed with officials of government and industry. Information thus obtained was appropriately analyzed by the use of propagation of variance formulas to determine the effect on estimates of cumulative exposure caused by the interacting variances of time and concentration data."

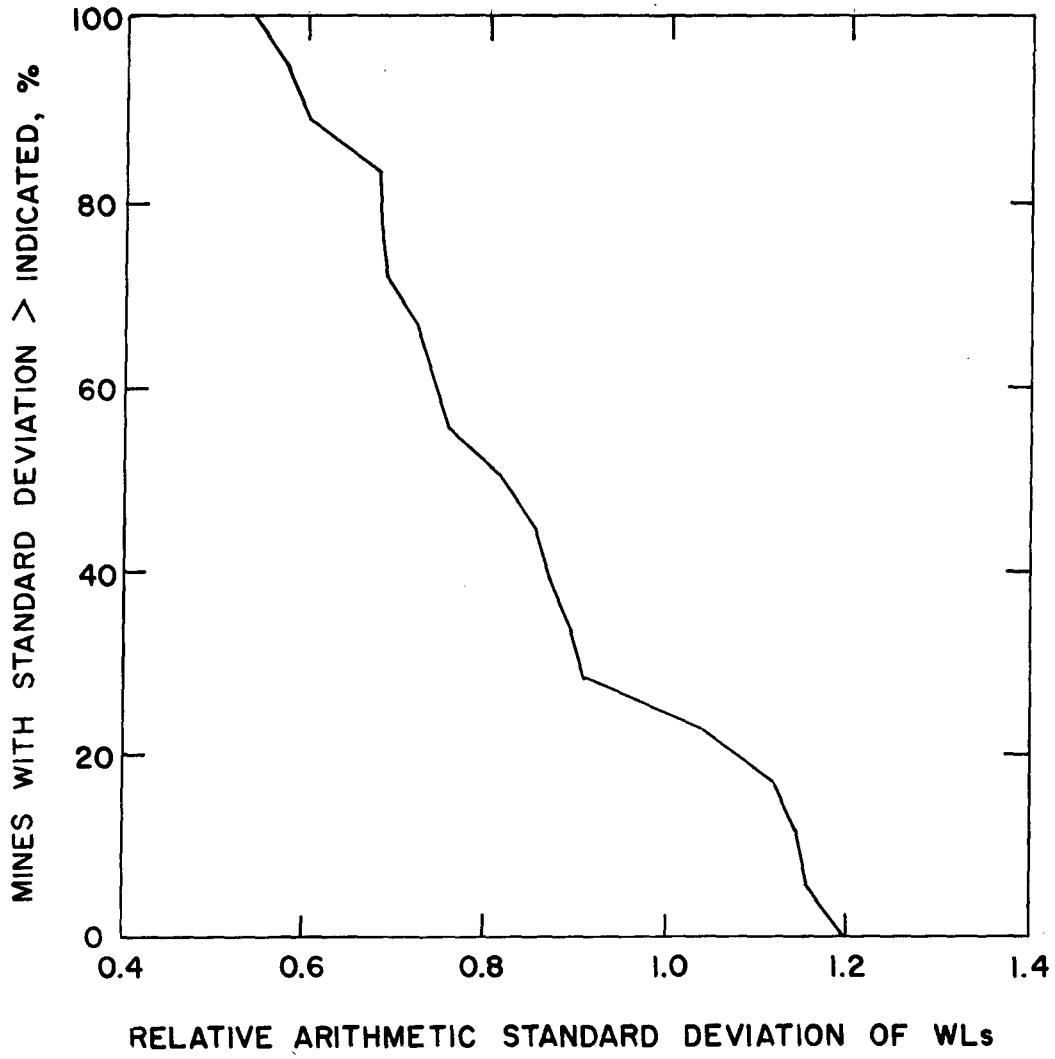

Figure 13: Cumulative frequency distributions of relative arithmetic standard of atmospheric concentrations of radon daughters in 19 uranium mines. (Breslin[3])

ing thermoluminescent dosimeters conducted by Colorado State University. The system described measured both external gamma ray exposures and cumulative WLM (or average WL).

White[5] described laboratory and field evaluations of four radon daughter and two radon dosimeters conducted by the United States Atomic Energy Health and Safety Laboratory. The Laboratory tests investigated separately the response of detectors to various radon daughter atmospheres and the performance of the pumps. Three of the four types of dosimeters performed satisfactorily in standardization tests. The report does not identify the dosimeters; however, the graphs of experimental results show the correlations between response and exposure for each device. Other necessary information such as the 70 percent and 95 percent confidence bands are also given. The dosimeters were also exposed to non-standard conditions, such as: low humidity, high humidity, high dust, unattached daughters, high velocity air flow or three-minute air. Under these conditions the responses of the dosimeters showed greater variations, but the tests were limited in extent and therefore the results were difficult to interpret.

Field tests of the dosimeters revealed many problems. None of the instruments performed satisfactorily with respect to accuracy and reproducibility. Correlations of response with ex-

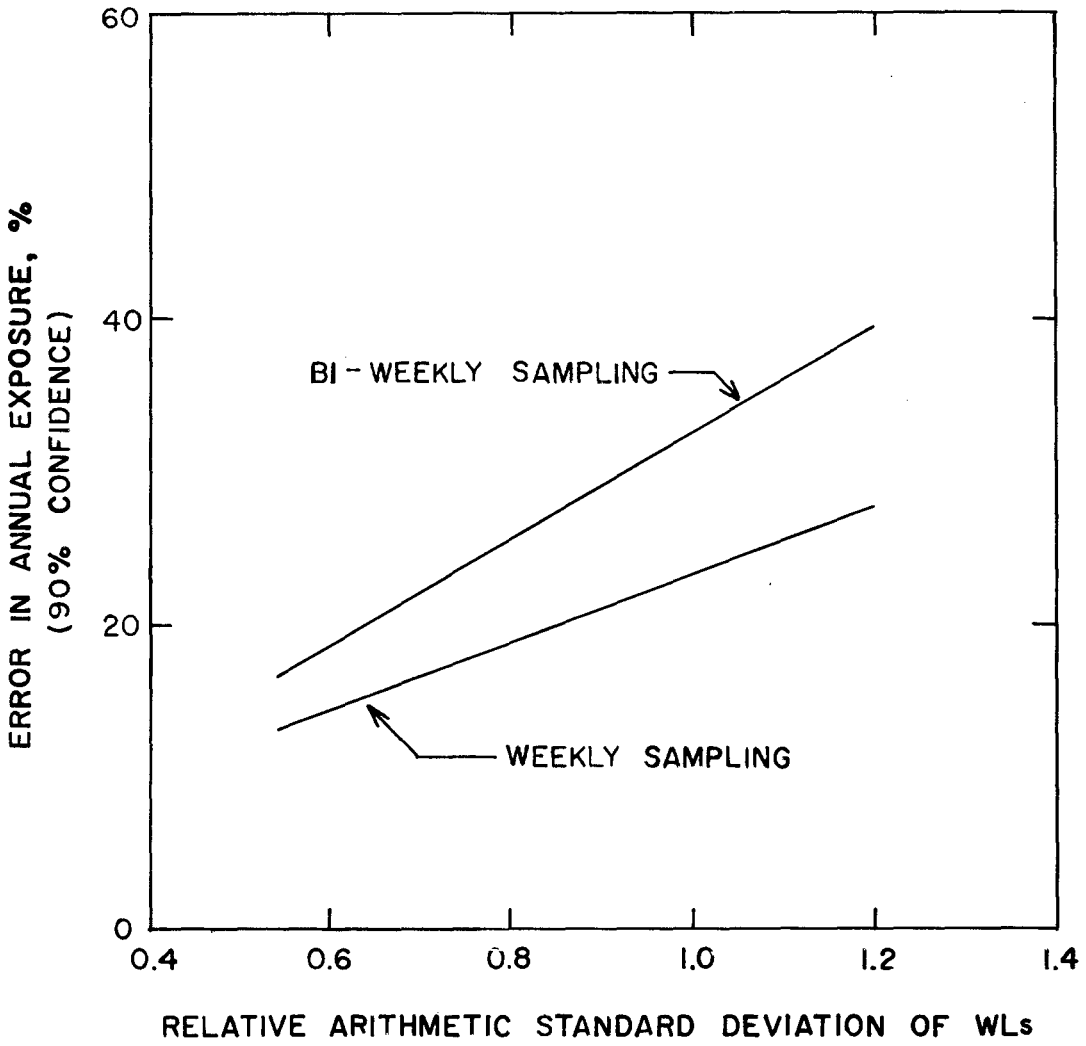

Figure 14: Error in annual exposure estimates vs. relative arithmetic standard deviations for weekly and bi-weekly sampling routines. (Breslin[3])

posure was weak and there was a wide scatter in the data. Malfunctions and losses were excessive for three of the dosimeters tested. The fact that three types performed as well as they did indicated that it might be possible to develop a reliable dosimeter based on one of the detection methods. It is apparent that much more work is required to produce devices which will not only perform satisfactorily in the laboratory but will operate under the much more arduous conditions which are prevalent in mines. Even if dosimeters which could be relied on only as area monitors were available, a great deal of monitoring time would be saved and better integrated exposure data would be obtained.

BIOASSAY

Any estimates of cumulative exposures which are derived from measurements of atmospheric concentrations and time-occupancy suffer from several serious defects. The most basic are variations in deposition and retention of radon daughters caused by physiological factors such as: rate and depth of breathing; degree of constriction of bronchi and bronchioles; and pulmonary clearance rates. No increase in frequency of air sampling or refinement of time studies can correct for such variations. These problems are also present in all situations where toxic materials are inhaled and have resulted in the devel-

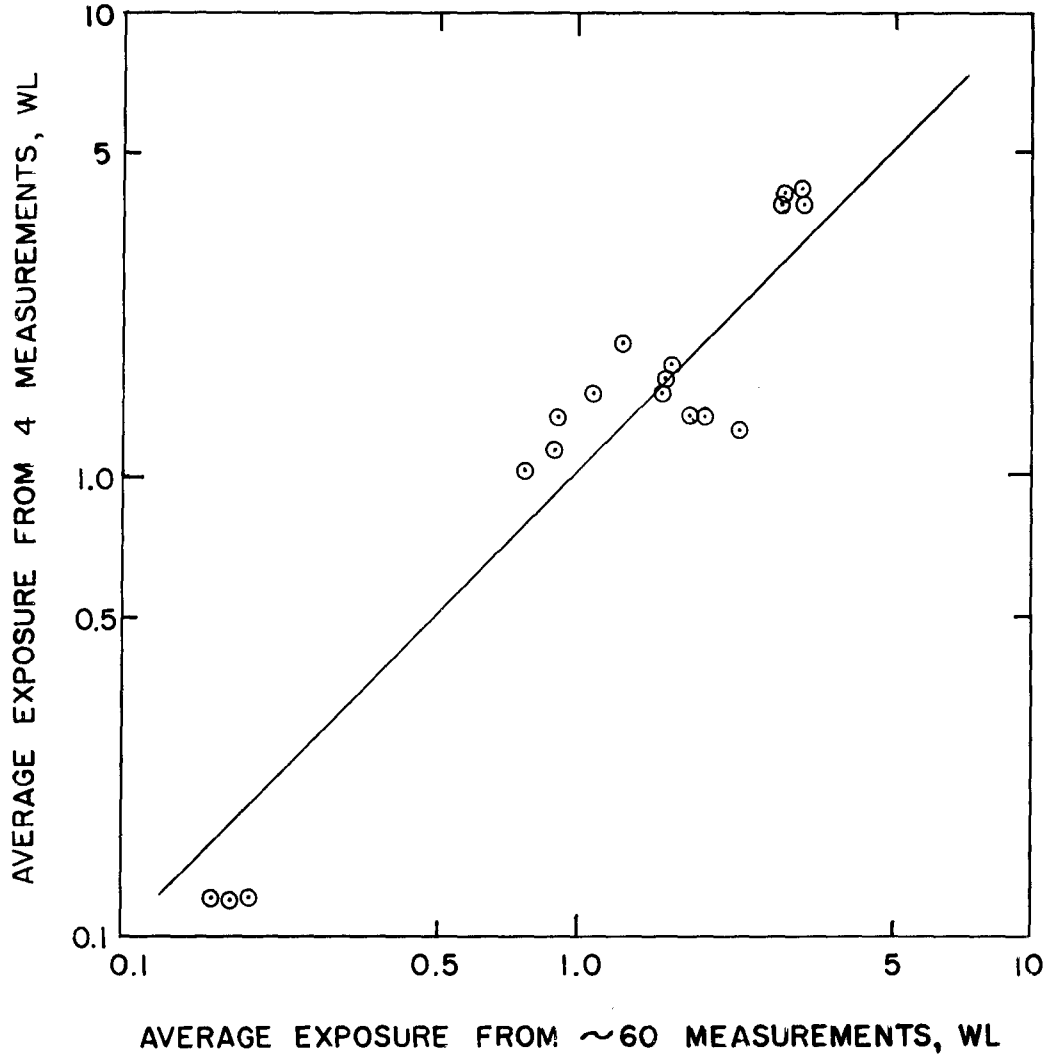

Figure 15: Miner exposure estimates from area-concentration and time-occupancy data vs. random miner-position concentration data.

opment of a large variety of bioassay procedures. Wherever a bioassay for a toxic substance is available it is considered to be a better measure of exposure, particularly cumulative exposure, than estimates derived from atmospheric concentration and occupancy data. This is true even though there may be wide individual variations in the metabolism of the substance in question.

Radon daughters have short half-lives and decay rapidly to ^{210}Pb which has a half-life of 19.7 years. This isotope of lead will, like stable lead, either be excreted promptly or be stored in body tissues, and so has been the subject of numerous investigations. Tissues and body fluids studied have been: urine, feces, blood, hair, whiskers, soft tissues and bone. Archer and Jensen[6] prepared a discussion of the significance of ^{210}Pb in uranium miners in which they summarized the findings of many of these studies. A list of the reports which they reviewed is included in the bibliography for this chapter. In their summary Archer and Jensen conclude that attempts to relate the concentration of ^{210}Pb in urine, blood, feces, hair, whiskers and soft tissues to the radiation exposure of uranium miners have been only qualitatively successful. This is because it has been impossible to separate the contribution to the ^{210}Pb burden of current exposure from that due to cumulative exposure. Additionally, the analytical procedures have been time-con-

suming and technically difficult. Bone ^{210}Pb concentrations have shown good correlations with estimated cumulative exposures, but this is not a routine monitoring procedure.

Eisenbud, Laurer, et al[27, 40] over the past several years have developed equipment capable of measuring low-energy x-rays produced by internally deposited radionuclides. As ^{210}Pb emits such x-rays, this group has conducted a series of laboratory and field studies to investigate the feasibility of using in-vivo measurements of skeletally deposited ^{210}Pb to estimate past exposures to radon daughters. In the present stage of development the procedures will detect the rough equivalent of 400 WLM cumulative exposures to radon daughters. In the 16 miners who have been followed for two years the highest body burden of ^{210}Pb found was 80 nanocuries (nCi). This miner developed lung cancer. These investigators stated that future improvements in design will increase the sensitivity of the system and permit better discrimination against beta and bremstrahling radiations.

If an external counting procedure suitable for extensive use could be developed, it would be a very valuable addition to the present methods of estimating individual exposures.

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PERSONAL PROTECTIVE DEVICES

INTRODUCTION

The first paragraph in the Respiratory Protective Devices Manual[1] states the rationale for use of such equipment succinctly in the following words:

> "In the control of those occupational diseases caused by breathing air contaminated with harmful dusts, fumes, mists, gases, or vapors, the primary objective should be to prevent the air from becoming contaminated. This is accomplished as far as possible by accepted engineering control measures; however, although one may wish to be idealistic in applying these procedures, there will always be circumstances in which, for one reason or another, the procedures will be uneconomical, inapplicable, impractical, or ineffective. Protective respirators will be needed for these situations, either as a primary means or as an adjunct or supplement to other primary control measures."

In uranium mining, conditions will occur in which engineering controls are impractical, inapplicable or ineffective. Occurrences which result in such conditions are: failure of an auxiliary fan; freezing up of a ventilation hole; and distruction of air stoppings by ground movement or concussion. Any events which reduce ventilation of a working area will result in a rapid increase in the atmospheric concentrations of radon daughters. If the concentrations exceed 2 WL, regulations require that the area be cleared and re-entry is not permitted until the concentration has been reduced below 1 WL. Those men who must enter to perform corrective work are required to wear respiratory protective devices. In addition to these emergency events, certain workers will frequently enter areas where the atmospheric concentrations of radon daughters exceed 1 WL. Mine geologists, mine surveyors, and those doing underground exploration are in this category. For these reasons respirators are a necessary part of a complete radiation control program.

AIR PURIFYING RESPIRATORS

American National Standard, Z88.1-1969, Radon Daughters[2] covers recommended procedures for respiratory protection against radon Safety Guide for Respiratory Protection Against daughters. Half-mask face-piece particulate air purifying respirators are the only types described by the standard, and for these a 90 percent overall efficiency as evaluated by man tests against radon daughters attached to mine aerosols is required. As mentioned in Chapter 4, radon daughters will be primarily attached to sub-micron aerosols and so filter materials should be evaluated under a range of actual mine conditions. It is quite possible for the efficiency of a media to vary widely depending on the size spectrum of the particulates in the mine atmospheric and the fraction of unattached radon daughter atoms. Tests of filter materials, both in the laboratory and in mines, were reported by Kaufman, Bevis and Hyatt.[3] Particulate filter respirators may be used in concentrations up to 10 WL. Self-powered particulate filter respirators were described by Burgess and Shapiro,[4] which have a small battery-operated blower to supply filtered air to the half-mask facepiece. They may be worn in higher concentrations because of less inward leakage around the facepiece. Self-powered devices equipped with hoods or facepieces are available.

AIR-SUPPLIED RESPIRATORS

Particulate filter respirators do not remove radon so their use is limited to atmospheres where the radon concentration is low enough so the lung radiation dose from this element is not a significant hazard. There is no agreement on what this level might be, but a value of 2,000 pCi of radon per liter (equivalent to 20 WL if radon is at equilibrium with its daughters) is used as a guide at the Denison Mine.[5] In those instances where men must enter areas where such high concentrations exist, they are equipped with a self-contained breathing apparatus. This practice is desirable and should be followed until information is available which will permit definition of the hazard produced by daughter-free radon.

ACTIVATED CARBON CANISTER RESPIRATORS

Self-contained breathing apparatus is cumbersome and permits only a limited working time. Thomas[6] has reported studies of the utility of activated carbon canisters for radon protection. The effects of temperature, humidity, radon concentration, carbon dioxide, and flow rate were investigated. The most significant variable was flow rate, as predicted by theory. The fraction of radon adsorbed was not affected by radon concentration over the range 1300-38,000 pCi/*l*. The Scott-Acme type 184-OV canisters removed about 99 percent of the radon from influent air over a one hour period at a flow rate of 16*l*/min., humidity of 9 mg/*l* and a temperature of 25°C. Thomas concluded that these canisters offered a weight advantage of at least a factor of 10 over self-contained breathing equipment. The canisters were regenerated by drawing uncontaminated air through them. The findings of this investigation indicate that activated carbon canisters could be a desirable alternative to self-contained breathing apparatus.

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GLOSSARY

Absorption: The process by which radiation imparts some or all of its energy to any material through which it passes.

Adsorption: The attachment of one substance to the surface of another.

Aetiological: See Etiological.

Alpha Particle (α): A positively charged particle (two neutrons bound to two protons) represented by the nucleus of a helium atom; very low penetrating power, but strong ionizing power, hence dangerous when deposited internally. Radon and several of its daughters are alpha emitters. Other radon daughters emit Beta and Gamma.

Alpha Ray: A synonym for alpha particle.

Alveoli: Plural of alveolus. Alveoli pulmonum, the air cells of the lungs.

Beta Particle (B): a negatively charged particle, with a mass of an electron. More penetrating but less ionizing than alpha particles; about 1/7500 the mass of an alpha particle. Numerous Betas are given off in the uranium decay chain.

Bioassay: A determination which measures a quantitative response of a biological cell or organism to whatever stress agent is applied. An example in the lung cancer context is the determination of the fraction of cells in the sputum which are abnormal. All chemical determinations of radioisotopes done on bodily fluids are bioassays.

Biological Threshold: The lower limit of stimulus capable of evoking a response in an irritable tissue.

Bone Seeker: Any compound or ion which migrates in the body preferentially into bone.

Bronchi: Plural of bronchus. The two main branches of the trachea.

Bronchial Epithelium: The membranous cellular tissue that forms the lining of the lungs.

Carcinogenic: Capable of producing cancer.

Carcinoma: Malignant neoplasm composed of epithelial cells, regardless of their derivation.

Carnotite: An uranium ore. A vanadate of uranium and potassium containing 50 to 65 percent of uranium trioxide, and about 20 percent of vanadium oxide. Found in Colorado Plateau as a yellow impregnation in sandstone.

CFM: Cubic Feet per Minute; one cubic foot equals 28.3 liters.

Collar: The mouth, or surface opening, of a mine shaft or bore hole.

Concentration: The relative content, in this instance, the relative amount of radon and its daughter products in the mine air. Practical measurement is in terms of the "working level," which see. (See also Maximum Permissible Concentration.)

Counter, Scintillation: The combination of phosphor, photomultiplier, tube and associated circuits for counting light emissions produced in the phosphors.

Curie (Ci): A quantity of radioactive material in which there are 3.7×10^{10} disintegrations per second; one micro curie (uCi) is 10^{-6} or one millionth of a curie; one pico curie (pCi) is a micro micro curie, or 10^{-12} curie.

Cytology: The subdivision of biology which deals with cells.

Cytoplasm: The protoplasm of a cell other than that of the nucleus, as opposed to nucleoplasm.

DPM: Disintegrations Per Minute. DPM equals number of atoms times decay constant.

Daughter: a synonym for decay product.

Decay Constant: The fraction, lambda (λ), of the number of atoms of a radioactive isotope which decays in the unit time. Lambda equals 0.693/half life.

Absorbed Dose: The quantity of energy imparted to a mass of material exposed to radiation (see RAD)

Cumulative Dose (Radiation): The total dose resulting from repeated exposures to radiation of the same region, or of the whole body.

Maximum Permissible Dose (MPD): Maximum dose of radiation which may be received by persons working with ionizing radiation.

Permissible Dose: The amount of radiation which may be received by an individual within a specified period with expectation of no significantly harmful result to himself.

Skin Dose (Radiology): Dose at center of irradiation field on skin. It is the sum of the air dose and backscatter; with the addition of the exist dose from other parts, if this is significant.

Threshold Dose: The minimum dose that will produce a detectible degree of any given effect.

[1]A portion of the glossary from PHS Pub. No. 494 is used here, appropriately updated and supplemented by certain new terms. USPHS "Radiological Health Handbook," USAEC DTI "Nuclear Terms—A Brief Glossary," and "Blakiston's New Gould Medical Dictionary, Second Edition" were the sources for the additional definitions.

Tissue Dose: Radiation dose received by a tissue in the region of interest.

Tolerance Dose: Synonym for "permissible dose". The latter is generally considered the preferrable term.

Dose Rate (Dosage Rate): Radiation dose delivered per unit time.

Dosimeter: Instrument used to detect and measure an accumulated dosage of radiation; in common use it is a pencil size ionization chamber with a built-in self-reading electrometer; used for personnel monitoring.

Downcast (Shaft): An opening extending to the surface through which outside air enters a mine.

Drift: A horizontal passage underground. A drift follows the vein as distinguished from a crosscut, which intersects it, or a level or gallery, which may do either.

Dyne: Force acting on a mass of one gram to produce an acceleration of one centimeter per second per second.

Electron Volt: A unit of energy equivalent to the amount of energy gained by the electron in passing through a potential difference of one volt. Larger multiple units of the electron volt are frequently used, viz: KeV for thousands or kilo electron volts: MeV for million electron volts and BeV for billion electron volts. (Abbreviated: ev) 1 ev $= 1.6 \times 10^{-12}$ erg.

Epidemiological: The sum of all the factors dealing with the incidence, distribution and control of a disease; e.g. studies relating human exposure to radon and its daughters to subsequent development of injury.

Epithelium: A term applied to cells that line all canals and surfaces having communication with external air and that are specialized for secretion in certain glands as the liver, kidneys, etc.

Equilibrium, radioactive: Among the members of a radioactive series, the state which prevails when the ratios between the amounts of successive members of the series remain constant.

Secular equilibrium: If a parent element has a very much longer half-life than the succeeding ones, so that there is no appreciable change in its amount in the time interval required for the later products to attain equilibrium; then, after the condition is reached, equal numbers of atoms of all members of the series disintegrate in unit time. This condition is never actually attained, but is essentially established in such a case as radium and its series to Radium D. The half-life of radium is about 1,600 years, of radon, approximately 3.82 days and of each of the subsequent members, a few minutes. After about a month essentially the equilibrium amount of radon is present, and then for a long time all members of the series disintegrate the same number of atoms per unit time.

Transient equilibrium: If the half-life of the parent is sufficiently short, so that the quantity present decreases appreciably during the period under consideration but is still longer than that of successive members of the series, a stage of equilibrium will be reached after which all members of the series decrease in amount exponentially with the period of the parent. An example of this is radon, with a half-life of approximately 3.82 days, and the successive members of the series to Radium D.

Erg: Unit of energy which can exert a force of one dyne through a distance of one centimeter.

Exposure: The product of radiant flux density multiplied by exposure time.

Acute exposure: Term used to denote radiation exposure of short duration.

Chronic exposure: Term used to denote radiation exposure of long duration by fractionation or protraction.

Face: In any tunnel or stope, the end at which work is progressing or was last done.

Geometry Factor: The fraction of the total solid angle about the source of radiation that is subtended by the face of the sensitive volume of a detector.

Half Life: Time required for a radioactive substance to lose by decay 50 percent of its activity.

Half Life, Biological: The time required for the body to eliminate one-half of an administered dose of any substance by regular processes of elimination. This time is approximately the same for both stable and radioactive isotopes of a particular element.

Histological: Relating to the branch of biology which deals with the minute structure of tissues; microscopic anatomy.

ICRP: International Commission on Radiological Protection.

Incidence Doubling Exposure Level: The level or range of exposure for uranium miners for which the estimated incidence of lung cancer may be twice as high as comparison group of non-mining males in the same geographical area.

Ionization: The process or the result of any process by which a neutral atom or molecule acquires either a positive or a negative charge.

Ionization Chamber: An instrument that detects and measures ionizing radiation by measuring the electrical current that flows when radiation ionizes gas in a chamber, making the gas a conductor of the electricity.

Ionizing Radiation: Radiation possessing sufficient energy to ionize the atom or molecules absorbing it.

Juno: A type of ionization survey meter currently used to measure the atmospheric concentration of radon daughters in mines. A known volume of air is pumped through a suitable filter paper; the alpha activity on the paper is counted at a measured time after sampling, and from this the radon daughter concentrations are calculated.

LET: Linear energy transfer: A measure of the

ability of biological material to absorb ionizing radiation; the radiation energy lost per unit length of path through a biological material. In general, the higher the LET value, the greater is the relative biological effectiveness of the radiation in that material.

LD50: Lethal Dose 50 percent. The radiation dose required to kill 50 percent of a relatively large number of animals.

Maximum Permissible Concentration (MPC): The amount of radioactive material in air, water, or food which might be expected to result in a maximum permissible dose to persons consuming them at a standard rate of intake. An obsolescent term.

Maximum Permissible Dose: (See under Dose.)

MEV: The symbol for 1 million electron volts, or 10^6 ev. (written MeV).

Microcurie (μCi) and Micromicrocurie ($\mu\mu$Ci); See Curie.

Micron: Unit of length equal to 10^{-6} meters.

Milliroentgen (mr): A submultiple of the roentgen equal to one one-thousandth (1/1000th) of a roentgen. (See Roentgen).

NCRP: National Committee on Radiation Protection.

Neoplasm: A new growth of cells which is more or less unrestrained and not governed by the usual limitations of normal growth. *Benign*: If there is some degree of growth restraint and no spread to distant parts. *Malignant*: If the growth invades the tissues of the host, spreads to distant parts, or both.

Picocurie: See Curie.

Pneumoconiosis: Chronic inflammation of the lungs caused by the inhalation of dust. All of the recognized forms are due to mineral dusts. Silicosis and asbestosis are the main forms of pneumoconiosis known to cause disability. Other forms, known as benign pneumoconiosis, are anthracosis, due to carbon dust, siderosis, due to iron dust, calcicosis, due to marble dust, and baritosis, due to barium dust.

Practical Threshold: The situation wherein a particular effect — in the present context it is the appearance of a malignancy — has an appearance time which is so long that it exceeds the normal life span. Thus, a person would die of normal cause before the malignancy would have the opportunity to affect the lifespan.

Rad: The unit of absorbed dose, which is 100 ergs/gram in any medium. The rad is a measure of the energy imparted to matter (i.e., retained by matter) by ionizing radiation per unit mass of irradiated material at the place of interest.

Radioactivity: Characteristic of certain kinds of matter, the atomic nuclei of which are unstable and undergo spontaneous disintegration with liberation of energy. The disintegration process, which usually results in the formation of new elements, is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma rays.

Radium A: Polonium-218. 9.87 atoms Po-218 equal one picocurie.

Radium B: Lead-214. 85.714 atoms Pb-214 equal one picocurie.

Radium C: Bismuth-214. 63.068 atoms Bi-214 equal one picocurie.

Radium C′: Polonium-214.

Radium D: Lead-210.

Radon: (Rn-222), a gas formed by the radioactive decay of radium 226 (which results from the radioactive decay of uranium 238). Radon escapes from exposed rock surfaces of mines or from mine water, into the air, where it continues to decay, generating a series of radioactive daughters. The latter are deposited in the lungs of miners, and are implicated as a probable cause of lung cancer. Principal radon daughters of interest are polonium 218, lead 214, bismuth 214, and polonium 214.

Raise: A vertical opening which connects one level of a mine with the level above.

RBE: (See Relative Biological Effectiveness.)

Recovery: The return toward normal of a particular cell, tissue or organism, after radiation injury.

Relative Biological Effectiveness (RBE): The RBE is a factor which is used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to different types of ionizing radiation. More specifically, it is the ratio of an absorbed dose of x-rays or gamma rays to the absorbed dose of a certain particulate radiation required to produce an identical biological effect in a particular experimental organism or tissue. This ratio is sometimes called the Relative Biological Efficiency Factor.

REM: (See Roentgen Equivalent Man.)

Roentgen: An exposure of X- or gamma radiation such that the associated corpuscular emission per 0.001293 grams of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign. (Abbreviated: r).

Roentgen Equivalent Man (rem): The rem is the unit used to express human biological doses as a result of exposure to one or many types of ionizing radiation. The dose in rems is equal to the absorbed dose in rads times the RBE factor of the type of radiation being absorbed. Thus the rem is the unit of RBE dose.

Sarcoma: Malignant neoplasm composed of cells imitating the appearance of the supportive and lymphatic tissues.

Scintillation Counter: (See Counter.)

Seam: A stratum or bed of coal or other mineral.

Secular Equilibrium: (See Equilibrium.)

Shaft: An excavation of limited area compared with its depth, made for finding or mining ore or coal, raising water, ore, rock or coal, hoisting and lowering men and material, or ventilating underground workings.

Sigmoid Curve: S-shaped curve, often characteristic of a dose-effect curve in radiobiological studies.

Somatic Cells: Body cells, usually having two sets of chromosomes, as opposed to germ cells, which have only one set.

Sputum: Material discharged from the surface of the air passages, throat, or mouth, and removed chiefly by spitting but in lesser degree by swallowing. It may consist of saliva, mucus, or pus, either alone or in any combination. It may also contain microorganisms, fibrin, blood or its decomposition products, or inhaled particulate foreign matter.

Squamous Metaplasia: Transformation or replacement of adult tissue by scalelike cells.

Stope: An excavation from which the ore has been extracted, either above or below a level, in a series of steps.

Stopping: A board, masonry or brick wall built across old headings, chutes, or airways, to confine the ventilating current to certain passages, and also to back up the gas in old workings, and in some cases to smother a mine fire.

Threshold Dose: (See Dose.)

Threshold Theory: As applied to the area of radiation dose-response relationship, the threshold theory acknowledges a certain minimum radiation insult before the biological repair mechanisms are overwhelmed. The *non*-threshold situation is one in which, no matter how small the radiation insult, there is some damage which is not repaired.

Time Weighted Exposure: An individual's exposure determined by multiplying the fraction of his working time spent in a given mine location by the working level concentration in that particular area.

Tolerance Dose: (See Dose.)

Transient Equilibrium: (See Equilibrium.)

Tumor: In its general sense a swelling. The term is often synonymous with neoplasm. Malignant Tumor: A tumor capable of metastasizing.

Upcast (Shaft): An opening extending to the surface through which air leaves a mine.

Working Level (WL): A level of concentration or burden of radioactivity in a given air environment. Related to environments containing radon and daughter products, a WL is represented by any combination of short-lived radon daughters in one liter of air that will result in the emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy from the radioactive decay of the radon daughters. This numerical value is derived from the alpha energy released by the total decay to RaD of the short-lived radon daughter products at radioactive equilibrium with 100 picocuries of radon 222 per liter of air.

Working Level Month (WLM): A unit of radiation exposure obtained from working in an environment of 1 WL for one month (170 hours). (For example, 12 months at 1 WL = 12 WLM; 12 months at 0.3 WL = 3.6 WLM). Most standards provide a further restriction on exposure, that no quarter of the work year shall involve greater than one-half the permissible annual total; e.g., in the first case above 6 WLM, in the second, 1.8 WLM.

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