T 1285

DETERMINATION OF RADON AND RADON DAUGHTERS IN UNDERGROUND URANIUM MINES

by

Jose A. Lampaya

T 1285

A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

Signed: _____
Jose A. Lampaya Valdes

Golden, Colorado
Date: March 20, 1970

Approved: _____
A. M. Keenan
Thesis Advisor

_____
A. M. Keenan
Head of Department

Golden, Colorado
Date: March 20, 1970

FOREWORD

This thesis is an investigation into current practices in determining radiation levels in underground uranium mines.

Part of the experimental data required in this investigation was obtained at one of the Kerr McGee mines and was used in the discussion of the equilibrium conditions between radon and radon daughters; but no comments or statements, either implicit or explicit, should be construed to refer to the practices, opinions, or policies of Kerr McGee Corporation.

The conclusions of this study are meant to be of general application, as this report is <u>not</u> a study of a specific mine.

ABSTRACT

This study deals with the determination of radiation levels in underground uranium mines.

Radiation conditions in a mine were investigated, and it was found that the determination of the state of radioactive equilibrium between radon and its daughter products is fundamental in assessing the exposure of personnel to radiation.

It was also found that in practice equilibrium is seldom attained underground. A numerical example showing how to calculate the concentration of radon daughters under non-equilibrium conditions is given.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The author wishes to express his appreciation and gratitude to the following:

Professor A. Keenan, Dr. J. Burnett and Professor N. E. Grosvenor, members of the thesis committee, for their guidance and encouragement during the course of this work.

Kerr McGee Corporation for authorizing this investigation in one of its mines.

Mr. J. Cleveland, Industrial Hygiene Supervisor, Kerr McGee Corporation, Grants, New Mexico, who made the necessary arrangements with the company for the author to carry out this work and for his guidance during the time spent at the mine.

Mr. M. Hill, Ventilation Technician, Kerr McGee Corporation, Grants, New Mexico, whose assistance, cooperation, and ideas were very helpful in making this work possible.

Mr. R. Rock, Mining Engineer, U.S. Bureau of Mines, Denver, Colorado, whose advice and discussions were very useful.

Mr. Leo Komar, Ventilation Engineer, U.S. Bureau of Standards, Denver, Colorado, whose references and encouragement were helpful.

All professors, students, and personnel of Colorado School of Mines who cooperated in any way in the development of this study.

OBJECTIVES

The research carried out and presented in this report was motivated by the situation encountered in uranium mines from the exposure of miners to the airborne radon progeny. The basic objectives of this paper are

a) General description of the problem,

b) Measurement of radon and radon daughter concentrations at the working places in a uranium mine,

c) Description of the monitoring techniques and equipment used,

d) Health and safety rules adopted.

INTRODUCTION

The continued development of the uranium industry has made necessary the extensive enlargement of underground mining operations to satisfy the demand for uranium ores. This made necessary an increase in the number of persons engaged in ore production from uranium mines and therefore the improvement of the safety systems in the mines.

From the beginning of the century, the inhalation and subsequent deposition of airborne radioactivity has been a definite health hazard always associated with the uranium mining industry. These radon daughters encountered in the atmospheres of underground uranium mines may be an occupational health hazard for those persons working in the mines.

At the present time the government formulated specific rules to deal with the problem, maintaining control of mine atmospheres to protect those persons involved in mining operations.

Industry is also engaged in setting rules doing its own policing to control underground atmospheres as government agencies simply do not have the manpower or time for day to day control.

Historical Background

The first historical evidence of the hazard by inhalation of radon and radon daughters comes from the regions of

Schneeberg, Germany, and from Joachimsthal in Czechoslovakia, between Saxony and Bohemia, where there are 14th- and 15th-century mines. Most of the miners engaged in these mines usually died of a lung sickness known in those days as the mountain sickness "Bergkrankheit."

Since the sixteenth century sources of information describing this type of illness have been encountered, which seemed to be always associated with those miners who had worked more than ten consecutive years in the mine.

In 1879 it was diagnosed by Hartung and Hesse as lung cancer, but it was not until 1930 that the radon was considered as the probable cause of lung cancer in miners.

Reported investigations from Pirchan and Sikl (1932) and a few years later by Peller (1939) show that in 60 autopsies performed the cause of death was lung cancer.

In 1951 Bale concluded that the highest contribution to the dose of radiation comes from the inhalation of the decay products of radon (radon daughters) rather than from the pure radon gas.

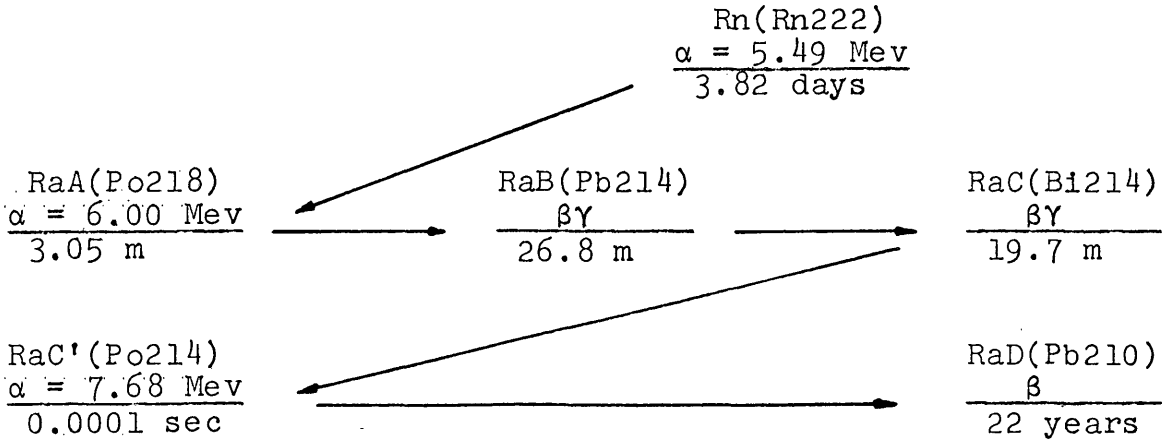
During the period January 1948 to December 1963 intensive research was carried out concerning this problem and these investigations indicate that the inhalation of high concentrations of radon daughters represents an occupational hazard for those persons engaged in the production of uranium ores.

RADON AND RADON DAUGHTERS

Uranium (U238) has a half-life period of 4,500 million years and supports a series of 13 lineal radioactive decay products. An atom of U238 develops a series of successive transitions until it is transformed into one of the non-radioactive and stable isotopes of lead (Pb206).

The fifth decay product of the U238 is radium (Ra226) which produces at a constant rate its daughter product radon (Rn222).

Radon is the only element in the uranium decay series which is a gas at ordinary temperatures. Due to this fact radon diffuses through the pores of the rock and escapes into the atmosphere where it continues to decay, generating its natural radioactive decay products, RaA, RaB, RaC, RaC', RaD. The sequence of disintegrations of radon can be represented by the following flow-chart.



Looking at the preceding chart, we can establish RaD (Pb210) as the natural end of the radon decay chain since its long half-life period (22 years) can be considered as stable in terms of months, weeks, days, hours, etc.

Along the decay chain of radon, all the nuclides (radon daughters) are solids, and they coat the surfaces which they contact; therefore, we can define this as a property which causes radon daughters to be potential hazards.

These products of radon decay, due to their atomic size, remain suspended in the air until decay occurs, or they adhere to other surfaces.

Physical Properties

Radon, which is a gas at ordinary temperatures, is only slightly soluble in water; and it has been determined experimentally that at 20°C, when the equilibrium state is reached, radon will be present in water at 0.23 times the concentration that it will have when air is in contact with it. The release of gas from water occurs rapidly, particularly if the water is agitated.

Radon is also soluble in fat, but the solubility is much more than in water, and it has been shown that at approximately 30°C a gram of olive oil retains 125 times more radon than the same volume of water.

The radioactive decay constant of radon is always 0.0075 per hour. Its half period is 3.82 days; its mean-

life is 5.50 days; the decrease in activity during a mean life is 0.368. The number of atoms in 100 pCi of radon is 1.77×10^{6} atoms, and therefore, the weight of 100 pCi of radon is 6.5×10^{-16} grams. Radon emits alpha radiation to produce its decay products, which are called radon daughters.

Radon daughters are products of the radioactive decay of Radon222 and are referred to as short-lived products. All these nuclides are solids and have the property of coating surfaces where they are deposited. These particles are atomic in size. They emit α and β particles and γ rays. Their half-lives and energy release characteristics have been described in the preceding flow-chart.

Radioactive Decay

In a radioactive substance the atoms always tend spontaneously to become stable due to the fact that radioactivity is the unstable state of the nuclei. This instability produces an emission or release of energy in the form of α or β particles and γ photons, during the whole process called disintegration or radioactive decay.

The original element or precursor is called the parent and the product of its decay the daughter, their relationship depending on the type of decay.

The rate of decay of any radioactive substance over a period of time obeys statistical laws applied to the number of disintegrations; therefore, the rate of decay is a

characteristic of the nuclide and is constant for a particular nuclide independent of its source.

Thus the rate of decay at any instant is always directly proportional to the number of radioactive atoms of the nuclide under consideration present at that instant and is given by the following equation:

$$-\frac{dN}{dt} = \lambda N \qquad (1.0)$$

where:

N = number of active atoms present.

t = time.

λ = decay constant or disintegration constant, in units of sec^{-1}.

The radioactive decay constant λ is a constant that is independent of all environmental conditions such as temperature, pressure, concentration, etc. The radioactive decay constant is measured in units of sec^{-1} and is related to the half-life period by the equation

$$\lambda t_{\frac{1}{2}} = 0.693 \qquad (1.1)$$

The rate of decay given by the product $I = N\lambda$ atoms per unit time is called activity.

The reciprocal of the decay constant (t_m) is called the average or mean life of the radioactive species and is represented by the equation:

$$t_m = \frac{1}{\lambda} . \qquad (1.2)$$

Integrating equation (1.0) from zero time, when the number of nuclides present is N_0, to a time t, when N of these nuclei remain, demonstrates that the decay follows an exponential law that can be represented by

$$N_t = N_0 e^{-\lambda t} \qquad (1.3)$$

where:

N_0 = No. of atoms present initially

N_t = No. of atoms present after a time t

e = (2.71828...)

λ = disintegration constant

t = elapsed time

Half-Life Period

The half-life period is the time required for a radioactive substance to decrease by decay to 50 percent of its initial activity.

From Eq. (1.3), if the value of N decreases to ½ of the initial value, the equation is transformed into

$$1/2 = e^{-\lambda t_{\frac{1}{2}}}$$

and therefore the half-life period can be represented by the following general formula

$$T_{\frac{1}{2}} = \frac{\log_e 2}{\lambda} = \frac{0.6931}{\lambda}$$

and in the case of radon the half-life period is

$$T_{\frac{1}{2}} = 0.6931 \left(\frac{1}{0.0075/hr}\right) = 92 \text{ hours.}$$

Therefore, the half-life period is directly proportional to the mean life (Eq. (1.2)) and inversely proportional to the decay constant, and thus can be written

$$T_{\frac{1}{2}} = 0.6931 \left(\frac{1}{\lambda}\right)$$

or

$$T_{\frac{1}{2}} = 0.6931 \text{ tm.}$$

Forms of Radiation

Alpha Radiation

Alpha particles are emitted by disintegration of certain radioactive substances, which are identical to the helium nuclei, having a mass of four atomic mass units (a.m.u.) and a positive charge of two units. Because of their relatively large size, they have little penetrating power and can be absorbed completely by filters.

Alpha particles can enter the body by inhalation or by ingestion of the radioactive material producing it.

Alpha radiation levels in uranium mines are determined by drawing a known volume of contaminated air through a filter collecting the particulate radon daughters and transforming the number of disintegrations per minute into working levels (see definition of working level on page 9).

Beta Radiation

Beta particles are given out by the majority of radioactive isotopes. A beta particle has a single negative charge and can be defined as a high speed electron emitted from a radioactive source. Its velocity approaches the velocity of light.

Gamma Radiation

A gamma ray is a short-length electromagnetic wave produced by radioactive decay. The gamma ray has no mass, but its energy destroys human tissue.

Units of Measurements

The unit used to measure the concentration of radiation generated by radon daughters is called the working level (WL). This unit, which was adopted in 1960 by the American Standards Association as an acceptable concentration in uranium mines, is based on a hypothetical equilibrium atmosphere and is defined as:

> One working level is any combination of the short-life decay products of radon (RaA, RaB, RaC, RaC') in 1 liter of air that will result in the ultimate emission by them of 1.3×10^5 Mev of alpha ray energy.

Exposure to radon daughters over a period of time may be expressed in terms of cumulative working level months (WLM),

1 WL x 173 Working Hours = 1 WLM.

The Picocurie

In radiation matters associated with the uranium industry, the activity is discussed in terms of picocurie units. One picocurie, also called micromicrocurie, is equal to 10^{-12} curie and equals 0.037 disintegrations per second.

In the uranium industry the activity is expressed in terms of 100 pCi.

100 pCi = 3.7 disintegrations/sec = 222 Dis/min.

Monitoring Techniques

In order to determine radon concentrations and radon daughters nowadays several techniques are in use, all of which are based on the same principles of sampling with variations in the methods and instruments used to interpret the samples.

Kerr McGee Corporation is very much interested in the control of radon gas and radon daughters in its mines and is continuously carrying out investigations to develop the most accurate procedures possible. The techniques, sampling methods, and the instrumentation used in this research are explained below.

Radon Sampling and Analysis

Radon concentrations were calculated by determining the alpha activity of a representative volume of filtered mine

atmosphere. In order to obtain the necessary data, air samples were collected by drawing 10 liters of mine air through a filter and through a 70-ml sampling flask (see flasks, p. 13) and by taking the ultimate volume of air enclosed in the flask as a representative sample. After a period of time, usually 3 hours, the gas was considered in equilibrium with the daughters and then the sample was ready for reading.

The flask (in which the alpha activity was converted by the coated surface to scintillations) was placed in a chamber coupled with a photomultiplier tube. These scintillations were converted into electrical impulses of a magnitude proportional to the number of photons striking the photocathode. These electrical pulses were amplified and recorded on a scale whose value corresponds to the activity or disintegrations per minute.

The 70-ml flask was estimated to be 90 percent efficient; therefore, in estimating the activity per liter of mine air, 15.87 times the activity of the flask should be considered.

The total alpha activity determined corresponds to the alpha emitters enclosed in the flask (Rn222, RaA, RaC') and therefore only 1/3 of the total activity (DPM) is produced by Rn222, thus to determine the Rn222 activity per liter

$$\text{Activity}_{\text{Rn222}} = \frac{15.87}{3} = 5.29$$

Therefore, the activity corresponding to the Rn222 per liter of air will be 5.29 times the activity of the sampled flask, or in the practical approach, the sampled flask was read for 5.29 minutes to get the total activity (DPM).

Radon Daughters Sampling and Analysis

Radon product concentrations were measured by determining the alpha activity of the deposition of the radon daughters on a fiberglass filter. For this purpose 10 liters of air were driven through the filter in 5 minutes sampling time (2 liters per minute pump rate), and these filters were collected as a representative sample.

The sample activity was determined between 40 and 90 minutes after the sampling, and the total number of the disintegrations per minute times the corresponding Kusnetz's factor (see Appendix I, page 44) determines the working level from the sample and therefore for the place where the sample was taken.

Instrumentation

The instruments used to collect and to interpret the radon and radon daughters samples taken at the mine are described below.

Flasks

In the collection of radon gas samples, 70-ml flask samples were used. Such flasks were coated with zinc sulfide activated with silver and quenched with nickel. The efficiency of the bottle was estimated to be about 90 percent.

Filters

Fiberglass GELMAN Type E filters were used to collect radon products. This type of filter was tested to a minimum of 99.7 percent efficiency for particles larger than 0.3μ as measured by the DIOCTYL PHTHALATE PENETRATION (DOP) test. The efficiency of this filter is above 98 percent for particles as small as 0.05μ. The heat tolerance of this filter is 230°C.

Alpha Activity Meter

In order to determine the alpha activity from the Rn222 and radon daughters samples, a laboratory meter was used with the following characteristics:

High-voltage power supply regulated and filtered to 0.01 percent ripple,

Photomultiplier tube, RCA type, no. 5819, coupled to zinc sulfide crystal for alpha disintegration detection,

Pulse amplifier connected to a read out,

Scalar capacity ±1 to 1,000,000 counts per second,

Automatic stop connected to a timer.

Pumps

In order to draw the required volume of air through the filter to collect the radon daughters, an M-S-A portable battery operated diaphragm pump was used. The flow rate was controlled by two valves and a sample flow indicator.

A sample inlet fitting was located on the top center of the pump case and was designed to accept two different diameters of sample inlet tubing. The sample inlet is connected directly with the flow-meter scale, and the flow was controlled by a dual valve assembly.

One of these valves directly controlled the air flow, while the other controlled the by-pass atmospheric air which might enter through the center of the stem. The flow was exhausted to the atmosphere through the fitting at the bottom of the case.

Wet Test Meters

In order to calibrate the pump rate to a fixed flow, Wet Test Meters are used. Such meters were designed to provide an accurate measure of the total volume of gas flowing through them and were installed between the gas source and the fixture or apparatus using the gas. These meters were calibrated according to ASTM D1071. The accuracy at time of calibration was within 0.5 percent.

MINE SAMPLING FOR RADON AND RADON DAUGHTERS

The experimental data required to carry out this investigation was obtained in one of the mines owned by Kerr McGee Corporation near Grants, New Mexico, during the period between October 1969 and January 1970.

Kerr McGee began exploring for uranium in the Ambrosia Lake area in 1955, and developed underground mining operations. In 1958 Kerr McGee constructed the uranium processing mill, considered the largest of its kind in the United States. The company operates six underground mines and has two more in development.

The mine in which this study was conducted is located in Ambrosia Lake, 6971 feet above sea level, the access to the mine being by means of a vertical shaft in sandstone, 752 feet deep. The drifts are driven horizontally into the boundaries of the ore body, and the ore is usually mined by the modified room and pillar method.

The mine is ventilated by two surface fans (downcast) having the characteristics below, and four smaller upcast fans on the surface.

Fan 1-33 (Two Fans in Series)

Fan #1

Diameter: 45 inch

H.P.: 125

Type: Axivane, Joy Series 1000

Number of Blades: 12 (set in 4th position)

Fan #2

Diameter: 45 inch

H.P.: 60

Type: Axivane, Joy Series 1000

Number of Blades: 12 (set in 4th position)

Operating Point:

H = 14.6 in w.g.

Q = 66.000 CFM

Fan 2-33

Diameter: 45 inch

H.P.: 125

Type: Axivane, Joy Series 1000

Number of Blades: 12 (set in 12th Position)

Operating Point:

H = 5.8 in w.g.

Q = 33.000 CFM

The ventilation system exhausts through the main shaft and four upcast surface fans.

Radon and Radon Daughters Sampling

In order to obtain the necessary information for determining the radiation conditions, air samples were taken in different parts of the stoping area studied. Radon and

radon daughters samples were collected simultaneously in order to study the relationship between the results, and therefore determine the equilibrium condition between the gas and daughters.

The places sampled were considered to be critical points in the mine with respect to mine activities, mine design, and the ventilation network, hence the average of the results may be taken as the average radiation value in the area sampled. The instruments and techniques used in sampling have been previously explained on page 12.

For sampling convenience the stoping area was divided into three sections (fig. 3) in order to control the radiation level more efficiently by ventilation.

The results from each of these sections are given in Appendix IV.

A total number of 66 samples were collected from the stoping area. Half of the samples taken consisted of filtered mine air to determine gas concentration and the other half radon daughters deposited in filters.

In all of these sections, air velocities and physical dimensions of the airways, cross section and length from one junction to another were recorded.

The volume of the airflow as well as plans of the stoping area showing airflow directions, ventilation inflows,

and all the calculations to determine radiation conditions are given in appendices II and IV.

Control of the Air Distribution

Computer Techniques

Since velocity and volumen are presently used for radiation control, exact determination of their values in the mine is necessary.

A computer program to determine the natural splitting of the airflow at the mine was developed, and the results obtained were checked by using a smoke tube and an anemometer. The values obtained by both methods matched those calculated by the computer program.

Mine Network

In the preparation of the input data to be used by the computer program the ventilation was defined using the following characteristics:

Drifts: The dimensions of the drifts have been considered as those in the mine, taking the average cross-section and length of each one from one junction to another. The friction factor taken for drifts was estimated at the mine, its value fluctuates between 100×10^{-10} and 110×10^{-10}.

Stopes: The friction factor for stopes was assumed to be the same as that for drifts.

Airflow: The volume of air entering the stopes was carefully measured at the end of the ventilation raises and the values obtained were considered as fixed quantity airflows in the computer program.

Mine Ventilation Equations

The method used in the program to solve the network was based on Atkinson's and Bernoulli's equations and Kirchhoff's laws by which resistances, head losses, and quantities were determined.

The following major formulas were used:

Bernoulli's equation:

$$\frac{P_1}{w} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{w} + \frac{V_2^2}{2g} + Z_2 + H_L \qquad (2.1)$$

where

$\frac{P}{w}$ = static energy

$\frac{V^2}{2g}$ = velocity energy

Z = potential energy

H_L = flow energy loss.

This equation can also be written

$$H_{T_1} = H_{T_2} + H_L \qquad (2.2)$$

where

H_T = total head.

Thus, equation (2.1) can be expressed

$$H_{S_1} + H_{V_1} + H_{Z_1} = H_{S_2} + H_{V_2} + H_{Z_2} + H_L$$

where

H_S = static head

H_V = velocity head

H_Z = potential head.

All pressures are expressed in inches water gage.

$$H_T = H_S + H_V$$

where

H_S = the energy consumed in the ventilation system to overcome all flow head losses (mine static head)

H_V = velocity head at the discharge of the system. It is considered a loss to the system in determining overall energy loss (mine velocity head)

And also from Atkinson's formula

$$H = \frac{KPLQ^2}{5.2A^3} \quad \text{or} \quad H = \frac{KSV^2}{5.2A}$$

$$R = \frac{KPL}{5.2A^3}$$

Therefore

$$H_L = H_S + H_V = \frac{KP(L+Le)Q^2}{5.2A^3}$$

where

K = friction factor

P = perimeter

L = length

A = area

Q = quantity of airflow in CFM.

The Computer Program

The computer program developed to calculate this type of problem is included as part of this report.

The numerical solution of the network studied has been included in appendix IV.

SAFETY AND HEALTH

The work of the safety and health programs has been recognized as an important part of personnel administration.

The emphasis upon safety originated in part from the prodding of federal and state laws, which prescribed minimum safety standards for occupations and type of business.

Labor unions also have bargained for improved safety of the worker on the job. Protection of the workers' health also has received attention from Government in some occupations.

Today most of the businesses have initiated their own programs of safety and health for both profit and humanitarian reasons.

The modern safety movement started around 1912 with the First Cooperative Safety Congress and the organization of the National Safety Council.

From that time remarkable advances have been made in reducing the rate and severity of such accidents and diseases, and obviously the result was an integration of employee-employer interests, in which economics had much to do with the safety movement.

Safety and Health Standards for Uranium Mines

U. S. Legislation

The safety and health standards for uranium mines have been a matter of discussion in recent years since it is intended to diminish the maximum radiation exposure of uranium miners.

The Department of Labor of the United States in the Federal Register, Volume 34, Number 96, page 7952, May 20, 1969, describes the safety and health rules to be applied in uranium mines as follows:

50-204.36 Radiation Standards for Mining

(a) For the purpose of this section, a "working level" is defined as any combination of radon daughters in 1 liter of air which will result in the ultimate emission of 1.3×10^5 million electron volts of potential alpha energy. The numerical value of the "working level" is derived from the alpha energy released by the total decay of short-lived radon daughter products in equilibrium with 100 pico-curies of radon 222 per liter of air. A working level month is defined as the exposure received by a worker breathing air at one working level concentration for 4 1/3 weeks of 40 hours each.

(b) (1) Occupational exposure to radon daughters in mines shall be controlled so that no individual will receive any exposure of more than 2 working level months in any calendar quarter and no more than 4 working level months in any calendar year. Actual exposures shall be kept as far below these values as practicable.

(2) In enforcing this section, the Director of the Bureau of Labor Standards may at any stage approve variations in individual cases from the limitations set forth in subparagraph (1) of this paragraph to comply with the requirements of the Act upon a showing to the satisfaction of the Director by an employer having a mine with conditions resulting in an exposure of more than 4 working level months, but not more than 12 working level months in any 12 consecutive months that (i) under

the particular facts and circumstances involved the working conditions of the employees so exposed are such that their health and safety are protected, and (ii) the employer has a bona fide plan to reduce the levels of exposure to those specified in subparagraph (1) of this paragraph as soon as practicable, but in no event later than January 1, 1971.

(3) Whenever a variation under subparagraph (2) of this paragraph is sought, a request therefor should be submitted in writing to the Director of the Bureau of Labor Standards, U.S. Department of Labor, Washington, D. C. 20210, within 90 days following the end of the calendar quarter or year, as the case may be.

(c) (1) For uranium mines, records of environmental concentrations in the occupied parts of the mine, and of the time spent in each area by each person involved in underground work shall be established and maintained. These records shall be in sufficient detail to permit calculations of the exposures, in units of working level months, of the individuals and shall be available for inspection by the Secretary of Labor or his authorized agents.

(2) For other than uranium mines and for surface workers in all mines, subparagraph (1) of this paragraph will be applicable: Provided however, that if no environmental sample shows a concentration greater than 0.33 working level in any occupied part of the mine, the maintenance of individual occupancy records and the calculation of individual exposures will not be required.

(d) (1) At the request of an employee (or former employee) a report of the employee's exposure to radiation as shown in records maintained by the employer pursuant to paragraph (c) of this section, shall be furnished to him. The report shall be in writing and contain the following statement:

This report is furnished to you under the provisions of the U.S. Department of Labor, Radiation Safety and Health Standards (41 CFR 50-204.36). You should preserve this report for future reference.

(2) The former employee's request should include appropriate identifying data, such as social security number and dates and locations of employment.

In addition to these rules and as an advance revision, the following specifications are proposed.

41-CFR 50-204.321 (36) Radiation Standards for Mining.

If a mine, at any working location therein, is above 4 WLM in any consecutive 12-month period or 2 WLM in any consecutive 3-month period, such mine must submit a request for variation to the Director of the Bureau of Labor Standards, U. S. Department of Labor, Washington, D.C. 20210, within 30 days after the end of the 3-month period or the year.

Variation request-contents:

1. Individual mine requests only will be considered.
2. The request shall include the following:
   a. All radiation levels in all working areas of the mine.
   b. Period of time covered (quarter or year).
   c. Number of employees of mine.
   d. Schematic of mine.
   e. Details of present ventilation (number of fans, downdraft or updraft).
   f. Volume of air to working areas, etc.
   g. Time necessary to make needed ventilation improvements.
   h. All other pertinent information.
3. The USDL will, prior to granting a variation, check the request through the Department's Denver District Office.

Variation granted-requirements:

1. Upon the granting of a variation, a mine will be required:
   a. To document that during the period granted each working place will be maintained at 1.0 WL environment or less to insure that 12 WLM will not be exceeded.

b. To furnish the Denver District Office (USDL) with monthly and accumulated year to date reports of exposure to employees.

c. To advise immediately the Denver District Office of any levels above 1.0 WL environment.

d. To advise the Denver District Office if the mine is closed for a period longer than one week and also to advise of reopening data.

Records

1. Each employer, regardless of size, is required to keep records of exposure. 41-204.36(c). Such records may be kept on USDL Forms CA-17 and CA-18 or in equivalent format. Weekly sampling should be conducted. Inspections made and records kept by State authority are not acceptable as the only sampling. However, such State sampling and the results if made available to the mine operator, may be substituted as a part of the total record.

   a. If a small operator does not have sampling equipment, the mill operator who purchases the ore for further processing to the AEC, shall be responsible for necessary sampling.

   b. For the purpose of determining individual exposure in a high WL place that is closed and the miner removed, the calculated exposure will be the average of the high sample found when closing and the low sample present at time of reopening. (Exception will be where daily or each shift sampling is accomplished).

   c. In calculating the WLM for an employee, only the time spent on the payroll or actual time in weekly fractions of a month will be acceptable, unless the employee's exposure from the immediate past employer is available and included in the exposure.

      (1) Where a mine is working a week and then closed down or the employee does not work, the records shall reflect the actual employee exposure and not be averaged along with the non-working time.

SAFETY REQUIREMENTS other than Radiation

The mine shall comply with the general safety requirements (laws, codes, regulations) of the State operated in. (41 CFR 50-204.1(d).

The mine shall also comply with the other general requirements of 41 CFR 50-204 where State mine law does not apply.

COMMENTS ON SOME ASPECTS DISCOVERED IN THIS STUDY

As a result of the work carried out to determine the causes of the problem at underground uranium mines, the circumstances contributing to the radioactive airborne products concentration considered most significant will be described below:

1) Type of rock bearing the ore, grade and type of ore.
2) Physical dimensions of the mining openings and of broken ore.
3) Airflow quantity, temperature, and humidity.
4) Velocity of the airflow.
5) Pressure drop and rate of release.
6) Age of the air.
7) Filters.
8) Equilibrium conditions.
9) Places of concentration.
10) Economics of the airflow.

These are the basic circumstances which appear at uranium mines, and a further explanation is included below.

Type of Rock Bearing the Ore, Grade and Type of Ore

The physical properties of the rock bearing the ore should be considered important since the pure radon gas

diffuses out of rock surfaces into any underground spaces, such as a mine.

The radon daughter products do not diffuse out of the rock because they are solids and isotopes of heavy metals.

Radon diffuses out because it is a chemically inert or noble gas, escaping through the pores of the rock. Therefore the rate of release will be, among others, a function of the porosity of the rocks and the types of ore.

Physical properties, humidity, temperature, pressure, grade, etc. should also be considered.

Physical Dimensions of the Mining Opening and of Broken Ore

The free spaces of the mine or airways should be considered, since they are fixed in dimensions at any given time and any change in the quantity of airflow will be reflected in the air velocity since one is a function of the other.

Also the breakage of ore produced at the stopes causes a sudden release of gas and increases the amount of gas in the stope atmosphere. Nevertheless, that gas is pure radon and thus it needs time to build up the daughter products and therefore may be removed by ventilation.

Quantity of Airflow, Temperature and Humidity

The volume of air entering the mine dilutes the radon gas and therefore this fresh airflow should be sufficient to dilute and transport radon safely through the mine openings during a maximum period of time which depends on the age of the air.

Temperature and humidity conditions do not affect radon characteristics since it is considered noble gas, and only very small changes occur associated with the daughter products. Nevertheless, such conditions should always be recorded when any study is carried out.

Velocity of Airflow

The velocity of the air-flow constitutes a currently practical way to remove the radon daughter products built up in underground mine atmospheres.

These atomic size particles can be transported by the airflow and exhausted out of the mine.

The air velocities should be controlled because of dust formation and also to make working places as comfortable as possible.

Pressure Drop and Rate of Release

It is clear that pressure affects radon emmanation rates, but further research is required to determine the precise relationships involved.

The Age of the Air

The importance of the age of the air in an effective ventilation system and in the economics of the air flow should always be considered in the design of mine ventilation network.

The elapsed time required for radon to build up the daughter products from a pure radon concentration is called age of the air. According to this concept the air flowing through the mine should be used until a time t_m in which the concentration of products built up overcome the permissible concentrations; after that moment it is necessary to filter the air to remove the daughter products or exhaust the air to surface.

Filters

Radon and radon daughter concentrations in the air can be diluted or filtered in order to maintain the permissible mine atmosphere.

By means of filtration, the radon products can be removed and retained in the filter, since they are solids and therefore amenable to filtration.

The filtered air can be used until radon daughters reach a permissible concentration level.

Equilibrium Conditions

Radioactive equilibrium is defined in the Radiological Health Handbook as "the state which prevails when the ratios between the amounts of successive members of the series remain constant." This equilibrium should be reached if no disturbance takes place at the mine, but several circumstances do not permit the production of equilibrium, the most important of which are

a) Quantity and velocity of the air through the mine openings,

b) Mine activities,

c) Release of gas from the rock.

Due to the fact that the radon products may be promptly removed by ventilation, the equilibrium condition is infrequently reached at the mine, and therefore Rn222 and its decay products may be considered in non-equilibrium conditions.

Places of Concentration

In those places where for any reason the radon has not been removed, such as in old stopes, drifts, raises, etc., the radioactive equilibrium can be approached.

For this reason all old operations or openings connected with actual operations should be sealed to prevent leakage of gas into the working places of the mine.

Concentrations of radon daughters in airways should be controlled to meet standards, and if radiation is above these standards, personnel should be withdrawn until ventilation corrections can be made.

Economics of the Airflow

In several cases the radiation conditions encountered in uranium mines have made economical operation impossible, since the ventilation requirements were too great.

For this reason it is necessary to control the ventilation system in such a way that the airflow will always be economic, and therefore a good ventilation design is fundamental.

CONCLUSIONS

As a result of the work performed for this thesis, the following conclusion has been reached.

Several approaches to the radiation exposure problem of underground uranium miners were considered and it was felt that by assuming 100 percent equilibrium conditions between radon and radon daughters, in determining radiation exposures, the real exposure may be overestimated.

If the equilibrium level between radon and radon daughters at the mine has been established as 20 percent, and if 100 percent is assumed for working level calculations then the real exposure will be overestimated by approximately 30 percent. Therefore the total accumulative dose will be 8.4 WL instead of 12 WL per year, as assumed using 100 percent equilibrium conditions.

Consequently the miner could be allowed to work at the mine at least 800 hours more without exceeding the permissible accumulative dose.

This fact establishes a direct relationship between safety and health, and manpower; the financial consequences of this relationship being obvious.

RECOMMENDATIONS

To determine radioactive exposure in underground uranium mines the following points must be considered:

1. The radioactive equilibrium conditions of the mine must be determined in order to calculate the real radioactive exposure.

2. In determining radiation exposures, the use of the method explained in Appendix I will be very useful since due to the long period of time allowed to read the samples, they can be re-read and checked before leaving the mine, or if a laboratory meter on surface is used, the allowed elapsed time allows one to leave the mine and to use the instrument at the laboratory.

3. In order to check the activity of samples at regular intervals, a sample should be read at least three times, at different times, and the average used. This should be done to correct for over or underestimations of the normal samples taken.

This does not constitute standard practice, but it is recommended when specific research is carried out or when manpower and time allows it.

4. To study by means of computer techniques, if the economy of the mine permits it, all the variations that the mine activity carries out in the ventilation system in order to correct any possible failure before it takes place.

A computer program that may be used is included in Appendix III.

APPENDIX I

EXPLANATION OF THE METHOD OF MEASUREMENT RECOMMENDED BY THE AUTHOR

APPENDIX I

EXPLANATION OF THE METHOD OF MEASUREMENT RECOMMENDED BY THE AUTHOR

As a main conclusion of this thesis, a new approach to the problem of determining radiation exposures of the uranium miners is suggested.

In order to give the maximum detail of the method it has been split into the following steps:

a) Determination of Rn222 concentrations at the mine,

b) Determination of the working level,

c) Determination of the equilibrium conditions,

d) Determination of the working level for 20 percent equilibrium in the mine atmosphere,

e) Computation of the working level factors of 20 percent equilibrium,

f) Comparison of the suggested method using 100 percent and 20 percent equilibrium conditions.

In the development of this method, the following assumptions have been made:

1) Constant concentration of Rn222 during filtering,

2) 100 percent efficiency of the filter retaining the radon daughters, and zero efficiency for retaining radon,

3) Constant rate of airflow through the filter in liters per minute,

4) The alpha activity counter has been calibrated with an RaC' source.

Determination of Rn222 Concentrations at the Mine

To determine the gas concentration, one should take a sample of filtered gas at the mine (usually 70 ml).

In filtered gas all the daughters have been removed, remaining on the filter, and only pure Rn222 will be in the bottle.

As soon as the Rn222 source has been removed (end of filtering), the gas in the bottle starts to decay, producing RaA, RaB, RaC, RaC', etc. Therefore activity from all of them is produced.

After some time has elapsed, the daughter products will be in certain conditions of radioactive equilibrium with the parent producing a total activity equal to $Rn222_{At} + RaA_{At} + RaB_{At} + RaC_{At} + \ldots + \text{etc.}$

If the total alpha activity at that specific time (A_t^{α}) is measured, the number of disintegrations per minute (DPM) will come from Rn222, RaA, and RaC' since they are the only short-life alpha emitters in the bottle.

To determine which is the DPM from each one of the nuclides, one must define the activity of 100 pCi as follows:

$$1 \text{ pCi} = 10^{-12} \text{ Curie} = 0.037 \text{ disintegration/sec}$$

$$100 \text{ pCi} = 3.7 \text{ DPS} = 222 \text{ DPM}$$

100 pCi/l of pure Rn222 produces 222 disintegrations per minute decaying at a rate of 0.0075/hour.

With the values of the activity of RaA, RaB, RaC (table 7), the total alpha activity per minute (DPM) from Rn222, RaA, and RaC' (alpha emitters) can be calculated for a concentration of 100 pCi/l.

Therefore if the DPM (alpha activity) from the sample taken at the mine (per liter of air after t_n minutes elapsed time) are different from those DPM from a 100 pCi/l sample at the same elapsed time t_n, the pCi/l in the former sample can be calculated by simple proportion, Table 9 (Appendix II).

Determination of the Working Level

The Joint Committee on Atomic Energy, Congress of the United States, defines a working level (WL) as follows:

> One WL is any combination of the short-lived decay products of radon (RaA, RaB, RaC, and RaC') in 1 liter of air that will result in the ultimate emission by them of 1.3×10^5 MeV of alpha-ray energy.

The meaning of this definition is expressed quantitatively in Table 1, below.

Table 1. Definition of the Working Level.

Nuclide	α-ray energy (MeV)	Half-period	Number of atoms per 100 pCi	Ultimate α-ray energy per atom (MeV)	Total ultimate α-ray energy (MeV/100 pCi)
Rn (Rn222)	5.49	3.82 days	1.77×10^6	excluded	none
RaA (Po218)	6.00	3.05 min	977	6.00+7.68	0.134×10^5
RaB (Pb214)	0	26.8 min	8580	7.68	0.659×10^5
RaC (Bi214)	0	19.7 min	6310	7.68	0.485×10^5
RaC'(Po214)	7.68	10^{-6} min	0.0008	7.68	$\underline{0.000 \times 10^5}$
Total					1.278×10^5

The numerical factor, 1.3×10^5 MeV, is derived from the α-decay energy ultimately delivered in the decay through RaC' of an initial mixture of 100 pCi each of RaA, RaB, RaC, and RaC', that is, of the short-lived decay products that are in radioactive equilibrium with 100 pCi of radon.

The actual method that was adopted to determine the working level (radon daughters concentration) and that was recommended by the Joint Committee on Atomic Energy Congress of the United States, Hearings, Ninetieth Congress First Session on Radiation Exposure of Uranium Miners (1967, p. 836, part II) is described as follows:

> As previously pointed out, the original field method gives results that are probably not seriously in error with regard to alpha energy released. However, the method is not accurate for expressing the results as micromicrocuries per liter of any isotropic species if secular equilibrium does not

exist among the immediate daughters of radon. For non-equilibrium conditions, the figures obtained by calculating from alpha disintegrations per minute to micromicrocuries per liter are only apparent concentrations which may be misinterpreted as real concentrations.

Maximum permissible levels for radon and radon daughters have usually been expressed in terms of activity as micromicrocuries per liter or microcuries per milliliter, such as "radon plus daughters, 10^{-7} microcuries per ml" (18). This procedure has been followed even though it is now recognized that the radiation dose from the radon alone in mixtures with its daughter products is relatively unimportant. See Section IV.

Such statements must be clearly defined to avoid confusion and, at best, refer to theoretical conditions which are rarely encountered in practice. However, if atmospheric concentrations of daughter products are expressed in terms of total alpha energy released, ambiguity is avoided, and it becomes unnecessary to attempt to determine the amounts of RaA, RaB, RaC present, a procedure which cannot be performed routinely in the field.

Such a method of calculation which measures alpha disintegrations per minute on a filter paper sample will give figures representing the potential alpha inhalation hazard and can be related directly to any reference level.

If 100 micromicrocuries each of RaA, RaB, and RaC per liter are taken as a suggested working level, it can be calculated from the data given in the earlier discussion of basic principles that the alpha energy released by the decay is one liter of this mixture through RaC' is 1.3×10^5 MeV. Such a mixture would give 112.6 disintegrations per minute on a filter paper one hour after collecting. Therefore, a meter reading showing 113 disintegrations per minute at 60 minutes will represent 1.3×10^5 MeV per liter of alpha energy.

A modification of the original field method based on these principles has been described (31) and is summarized below. In this procedure, factors for calculating from alpha dpm to MeV/l were determined by solving Bateman-type equations for the decay of various equilibrium and nonequilibrium mixtures. These factors are given in figure (V-5), and the errors in estimating the alpha energy per liter are listed in table V-5. The method is as follows:

1. Collect a measured air sample on filter paper as given in the original method.
2. Measure the alpha dpm from 40 to 90 minutes after the end of sampling.
3. Calculate the alpha dpm per liter of air sampled.
4. Divide the dpm per liter by the factor from figure V-5.
5. The resultant figure gives the multiple or fraction of the suggested working level (1.3×10^5 MeV) existing in the air. Multiply this figure by 1.3×10^5 to determine the amount of potential alpha energy in MeV per liter of air.

H. L. Kusnetz (1956, p. 85, 88) describes a method for determining radon daughters concentrations in mine atmospheres and calculates the factors which are in use today. This is considered the most accurate method.

Nevertheless Kusnetz says: "This technique assumes equilibrium conditions between the daughters," and it has been demonstrated that the equilibrium condition is never reached in mine atmospheres.

Kusnetz's factors are included in figure 1(V-5) below. With this method and with the assumption of equilibrium conditions among the daughters, the working level values for the samples taken have been calculated and are shown in tables 10 to 15 (Appendix IV).

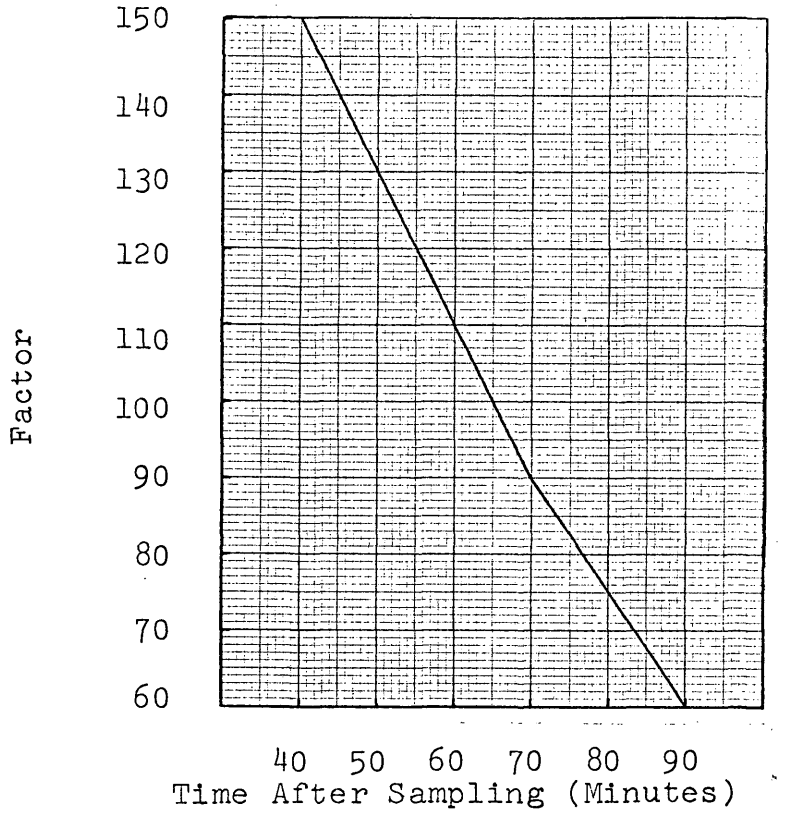


Figure 1 (V-5). Factor time relationship for determining percentage of WL of radon daughter products in atmosphere.

Determination of the Equilibrium Conditions

The concentration of pCi per liter and the working level values for the samples taken at the mine have been calculated by the preceding methods.

With one set of samples from the same location of the mine, the equilibrium conditions have been computed according to the following procedure.

At equilibrium conditions it has been determined by the definition of working level (p. 40) that, to produce an ultimate emission of α energy of 1.3×10^5 MeV from 1 liter

of air containing RaA, RaB, RaC, and RaC', an activity of 100 pCi is needed, and therefore in radioactive equilibrium for each 100 pCi/l there is 1 working level.

As an example, for sample No. 2 (Table 14, Appendix IV) the activity is 120 pCi/l of air; thus, if the 100 percent equilibrium conditions are assumed, the value of the working level for this sample should be 1.2 WL, but instead of 1.2 WL, the calculated value is only 0.101 WL. Using the following expression one can calculate the percent of equilibrium,

$$\% \text{ Equilibrium Sample No. 2} = \frac{100 \times 0.101}{1.2} = 9\%.$$

By the same procedure with all the samples, the percent of equilibrium in all of the sampling places have been determined. The average value ($\bar{x}$) of these percents could be taken as the percent of equilibrium of the sampled section of the mine. To illustrate the method, the results for one of the sampled areas of the mine are included below.

Sample	Junction	Working Level	PCi/L	Percent Equilibrium
1	34	0.668	328.0	20.366
2	42	0.630	373.0	16.890
3	37	0.554	373.0	14.853
4	38	0.485	311.0	15.595
5	39	0.903	330.0	27.364
6	36	0.622	354.0	17.571
7	35	0.561	451.0	12.439
8	41	0.719	299.0	24.047
9	40	0.515	635.0	23.858
10	4000	0.740	831.0	20.939
11	43	0.840	390.0	21.538
12	45	0.652	599.0	10.885
13	5000	0.876	293.0	29.898

Determination of the Working Level for 20% of Equilibrium in the Mine Atmosphere

The first step in this procedure is to determine which is the activity of RaA, RaB, RaC for 20 percent equilibrium.

Evans (1968, p. 387, fig. 100) determines the growth of working levels in initially pure radon, giving the following example to show the use of these values: "If the average residence time of radon underground is 20 minutes, then fig. 100 shows that only 30% of the equilibrium decay product working levels can be developed underground."

It has been calculated that the equilibrium condition at the mine is only 20 percent. By the same procedure it is found that the activity for 20 percent equilibrium corresponds approximately to 12 minutes old air (see fig. 2, Appendix II). The numerical values of the activity at 12 minutes are taken from Table 7 (Appendix II):

Time	RaA	RaB	RaC
12	93.5%	18.2%	2.87%

Knowing the activity at 20 percent of equilibrium, one can determine the delivery energy at such conditions because the activity is proportional to the number of atoms (Kaplan, 1962, p. 215), and therefore

$$\frac{N(t_1)}{N(t_2)} = \frac{A(t_1)}{A(t_2)}$$

where

N = number of radioactive atoms

A = activity

t = time

therefore

$$N(t_2) = \frac{N(t_1) \times A(t_2)}{A(t_1)}$$

$$N_{A20\%} = \frac{977 \times 93.5}{100} = 913$$

$$N_{B20\%} = \frac{8580 \times 18.2}{100} = 1561$$

$$N_{C20\%} = \frac{6310 \times 2.87}{100} = 181$$

where

$NA_{20\%}$, $NB_{20\%}$, $NC_{20\%}$ = Number of atoms of RaA, RaB, and RaC respectively per liter of air at 20% equilibrium per 100 pCi/l.

At 20 percent of equilibrium, the calculated energy from the daughters is also 20 percent of the energy of air containing 100 pCi/l at 100 percent equilibrium conditions.

To deliver the energy of 1 WL (1.3×10^5 MeV) from this mixture of air at 20 percent equilibrium, one must increase the number of atoms 5 times, in which case the activity will be equivalent to 500 pCi/l.

For these new conditions (500 pCi/l) the following values have been calculated in Table 3.

Consequently, the definition of working level, given on

page 40 is also adequate in this case.

Table 2. Total ultimate α energy for 20 percent equilibrium (100 pCi/l).

Nuclide	Number of Atoms per 100 pCi	Ultimate α-Ray Energy per Atom (MeV)	Total Ultimate α-Ray Energy (MeV/100 pCi)
RaA	913	13.68	0.12489×10^5
RaB	1561	7.68	0.11988×10^5
RaC	181	7.68	0.01390×10^5
RaC'	000	7.68	0.00000×10^5
Total			0.25867×10^5

Table 3. Total ultimate α energy for 20 percent equilibrium (500 pCi/l).

Nuclide	Number of Atoms per 500 pCi	Ultimate α-Ray Energy per Atom (Mev)	Total Ultimate α-Ray Energy (MeV/500 pCi)
RaA	4665	13.68	$.62449 \times 10^5$
RaB	7805	7.68	$.59942 \times 10^5$
RaC	905	7.68	$.07040 \times 10^5$
RaC'	000	7.68	$.00000 \times 10^5$
Total			1.30431×10^5

In determining the value of the factors to be used under mine conditions (20 percent equilibrium) - values that are used in computing levels - it is necessary to calculate the number of disintegrations that this number of atoms will produce in different times, and from them compute the factors. One of the procedures used to calculate the activity (disintegrations per minute, DPM) is the summation rule, which is explained in detail by P. Groer, R. D. Evans, and G. L. Schroeder on page 335 of MIT-952-5 Annual Progress Report to the Atomic Energy Commission, At (30-1) 952 (Physics Department, Radioactivity Center, Massachusetts Institute of Technology). This procedure is explained as follows:

> To estimate the decay of activity on a filter after sampling, one uses the summation rules (see Sec. E8). Let t_S denote the sampling time and t_E the decay time (time after end of sampling). Then the summation rules state:
>
> [Activity after sampling for t_S minutes and subsequent decay without sampling for t_E min.] = [Activity if sampling could continue for (t_S+t_E)min.] - [Activity if sampling would last only for t_E min.]
>
> It can be shown by using the appropriate solutions of the Bateman equations that this procedure gives the exact activity for any build-up time t_S and any decay time t_E. The use of the summation rules is not an approximation.

What is meant can be illustrated and clarified by an example using the values in Table 8 to establish the following:

t_S = Sampling time (10 minutes)

t_E = Elapsed time (50 minutes)

S_V = Sample volume (10 liters)

P_R = Pump Rate (1 liter/minute).

{Activity at (t_S(10)+t_E(50))min.} - {Activity at t_E(50)min.}

100% Equilibrium

	RaA	RaB	RaC
RaA	(1.000-1.000)977		
RaB	--		
RaC	(.497-.398)977	(.5362-.4419)8580	(.8789-.8278)6310

Total (.099 x 977) + (.0943 x 8580) + (.0511 x 6310)=1228 DPM

20% Equilibrium

	RaA	RaB	RaC
RaA	(1.000-1.000)4565		
RaB	--		
RaC	(.497-.398)4565	(.5362-.4419)7805	(.8789-.8278)905

Total (.099 x 4565) + (.0943 x 7805) + (.0511 x 905)=1234 DPM

Due to the fact that the half-life period of RaC' is very short (1.60×10^{-4} sec), RaC will be considered as if it were responsible for the RaC' alpha emission, since the decay of each RaC atom takes place practically instantaneously by the alpha decay of RaC'; therefore the RaC' alpha emission may be considered, for mathematical purposes, as if it originated in the decay of RaC.

By use of the same procedure, the following values for different times have been calculated in Table 4 below.

Table 4. Determination of the total alpha activity for 100 percent and 20 percent equilibrium.

Elapsed Time (min.)	TOTAL ALPHA ACTIVITY (DPM)	
	100% Equilibrium 100 pCi/liter	20% Equilibrium 500 pCi/liter
50	1228	1234
60	1019	1074
70	839	921
80	684	771
90	554	641

From the values in Table 4, the factors for interpretation of disintegrations per minute in terms of working levels have been calculated and shown in Table 5 below.

Table 5. Factors for Interpretation of DPM in terms of working levels.

Elapsed Time (min.)	F A C T O R	
	100% Equilibrium	20% Equilibrium
50	0.000815	0.000811
60	0.000982	0.000931
70	0.001192	0.001086
80	0.001462	0.001297
90	0.001806	0.001560

Numerical Comparison of the Described Method Using 100 and 20 Percent Equilibrium Conditions

The two equilibrium conditions for determining radon daughter concentrations in mine atmospheres will be compared theoretically, based on 100 percent and 20 percent equilibrium.

The individual values were computed separately for the two equilibrium conditions as follows:

1. If an activity of 5,000 DPM is used to estimate the working level value by the recommended method, considering 100 percent equilibrium, the value will be

$$5{,}000 \times 0.000815 = 4.1 \text{ WL.}$$

If now, only the 20 percent equilibrium condition is considered, the value will be

$$5{,}000 \times 0.000811 = 4.0 \text{ WL.}$$

By the same procedure, the values for 5,000, 3,000, 2,000, and 1,000 disintegrations per minute at 50, 60, 70, 80, and 90 minutes elapsed time have been calculated (in terms of working levels) and shown in Table 6 below.

2. By use of a sample of mine activity, the working level values were computed separately for 20 percent and 100 percent equilibrium conditions.

These samples were read at different elapsed times, and the corresponding activities were expressed in terms of working levels. The numerical results are included in Table 6 below.

3. By use of a constant theoretical activity of 1,000 DPM, the potential alpha energy in terms of working levels has been calculated, and the results are shown in Table 6.2 below.

Table 6. Numerical Comparison Between 100 and 20 Percent Equilibrium Conditions.

Elapsed Time (min.)	5000 DPM		3000 DPM		2000 DPM		1000 DPM	
	100% Equ.	20% Equ.	100% Equ.	20% Equ.	100% Equ.	20% Equ.	100% Equ.	20% Equ.
50	4.1	4.0	2.4	2.4	1.6	1.6	.8	.7
60	4.1	3.9	2.4	2.3	1.6	1.5	.8	.7
70	4.1	3.7	2.4	2.2	1.6	1.5	.8	.7
80	4.2	3.7	2.5	2.2	1.6	1.4	.8	.7
90	4.1	3.6	2.4	2.1	1.6	1.4	.8	.7
Σ	20.6	18.9	12.1	11.1	8.0	7.5	4.0	3.5
$\bar{x}$	4.12	3.78	2.42	2.24	1.60	1.50	.8	.7

Table 6.1 Determination of the Working Level Values from a Mine Sample.

Elapsed Time	DPM	100% Equilibrium	20% Equilibrium
60	720	.71	.67
80	544	.79	.70
100	370	.85	.57
120	188	.66	.37
140	138	.77	.50
160	112	1.00	.64
180	86	.99	.76
$\bar{x}$		.82	.60

Table 6.2 Theoretical Determination of the Working Level Values Using a Constant Activity of 1000 DPM.

Elapsed Time	DPM	100% Equilibrium	20% Equilibrium
50	1000	.81	.81
60	1000	.98	.93
70	1000	1.19	1.08
80	1000	1.46	1.30
90	1000	1.80	1.56
130	1000	4.46	2.92
180	1000	11.49	8.85

APPENDIX II

TABLES AND FIGURES

Time Minutes	Ra A (Po 218)	Ra B (Pb 214)	Ra C (Bi 214)
0.5	0.1074	0.000706	0.00000417
1	0.204	0.00277	0.0000322
2	0.366	0.0101	0.0002396
3	0.495	0.0210	0.000755
4	0.598	0.0345	0.00167
5	0.680	0.0500	0.00352
6	0.745	0.0670	0.00550
7	0.797	0.0851	0.00801
8	0.838	0.104	0.0111
9	0.871	0.123	0.0147
10	0.898	0.143	0.0188
11	0.918	0.162	0.0235
12	0.935	0.182	0.0287
13	0.948	0.201	0.0344
14	0.959	0.220	0.0406
15	0.967	0.239	0.0472
16	0.974	0.258	0.0542
17	0.979	0.276	0.0617
18	0.983	0.295	0.0695
19	0.987	0.312	0.0776
20	0.989	0.329	0.0861
25	0.997	0.410	0.132
30	0.999	0.482	0.184
35	1.000	0.545	0.237
40	1.000	0.600	0.292
45	1.000	0.648	0.346
50	1.000	0.691	0.398
55	1.000	0.729	0.449
60	1.000	0.762	0.497
70	1.000	0.816	0.584
80	1.000	0.858	0.660
90	1.000	0.890	0.724
100	1.000	0.915	0.778
110	1.000	0.935	0.822
120	1.000	0.950	0.858
130	1.000	0.961	0.887
140	1.000	0.970	0.910
150	1.000	0.977	0.929
160	1.000	0.982	0.944
170	1.000	0.986	0.956
180	1.000	0.989	0.966

Table 7. Numerical Values for the Growth of Activity of Ra A, Ra B, Ra C from a Radon Source (R. D. Evans, R. J. Kolenkow, 1968).

Time Minutes	Ra A	Ra C-A	Ra C-B	Ra C
0.5	0.1074	0.00000417	0.0001125	0.01744
1	0.204	0.0000322	0.0004457	0.03457
2	0.366	0.0002396	0.001747	0.06794
3	0.495	0.000755	0.003852	0.1002
4	0.598	0.00167	0.006712	0.1313
5	0.680	0.00352	0.01028	0.1613
6	0.745	0.00550	0.01451	0.1903
7	0.797	0.00801	0.01936	0.2183
8	0.838	0.0111	0.02478	0.2453
9	0.871	0.0147	0.03075	0.2714
10	0.898	0.0188	0.03722	0.2966
11	0.918	0.0235	0.04415	0.3209
12	0.935	0.0287	0.05152	0.3444
13	0.948	0.0344	0.05929	0.3670
14	0.959	0.0406	0.06743	0.3889
15	0.967	0.0472	0.07591	0.4100
16	0.974	0.0542	0.08470	0.4304
17	0.979	0.0617	0.09378	0.4501
18	0.983	0.0695	0.1031	0.4691
19	0.987	0.0776	0.1127	0.4875
20	0.989	0.0861	0.1225	0.5052
25	0.997	0.132	0.1740	0.5850
30	0.999	0.184	0.2281	0.6519
35	1.000	0.237	0.2831	0.7081
40	1.000	0.292	0.3376	0.7552
45	1.000	0.346	0.3908	0.7947
50	1.000	0.398	0.4419	0.8278
55	1.000	0.449	0.4905	0.8556
60	1.000	0.497	0.5362	0.8789
70	1.000	0.584	0.6188	0.9148
80	1.000	0.660	0.6894	0.9401
90	1.000	0.724	0.7488	0.9578
100	1.000	0.778	0.7980	0.9703
110	1.000	0.822	0.8384	0.9791
120	1.000	0.858	0.8712	0.9853
130	1.000	0.887	0.8978	0.9897
140	1.000	0.910	0.9191	0.9927
150	1.000	0.929	0.9361	0.9949
160	1.000	0.944	0.9497	0.9964
170	1.000	0.956	0.9605	0.9975
180	1.000	0.966	0.9690	0.9982

Table 8. Accumulation of Airborn Ra A and Ra C in a Filter (R. D. Evans, R. J. Kolenkow, 1968).

Table 9. Alpha Activity (DPM) from 100 pCi/liter of Rn222 Source and Correction Factors.

Time Min.	Rn+RaA+RaC' Activity (CPM)	Correction Factor	Time Min.	Rn+RaA+RaC' Activity (CPM)	Correction Factor	Time Min.	Rn+RaA+RaC' Activity (CPM)	Correction Factor
.5	246	0.4065	25	473	0.2114	200	650	0.1538
1	267	0.3745	30	484	0.2066	210	649	0.1541
2	303	0.3300	35	495	0.2020	220	648	0.1543
3	332	0.3012	40	508	0.1968	230	648	0.1543
4	355	0.2817	45	520	0.1923	240	647	0.1545
5	374	0.2674	50	530	0.1887	250	646	0.1548
6	388	0.2577	55	541	0.1848	260	645	0.1550
7	401	0.2494	60	552	0.1811	270	644	0.1552
8	410	0.2439	70	572	0.1748	280	643	0.1555
9	418	0.2392	80	588	0.1700	290	642	0.1559
10	425	0.2353	90	603	0.1658	300	642	0.1559
11	431	0.2320	100	612	0.1634	310	641	0.1560
12	436	0.2293	110	622	0.1608	320	640	0.1562
13	440	0.2273	120	630	0.1587	330	639	0.1565
14	443	0.2257	130	637	0.1570	340	638	0.1567
15	447	0.2237	140	642	0.1559	350	637	0.1570
16	450	0.2222	150	646	0.1548	360	637	0.1570
17	453	0.2207	160	647	0.1545	370	636	0.1572
18	455	0.2198	170	650	0.1538	380	636	0.1572
19	458	0.2183	180	652	0.1534	390	635	0.1575
20	461	0.2169	190	651	0.1536	400	635	0.1575

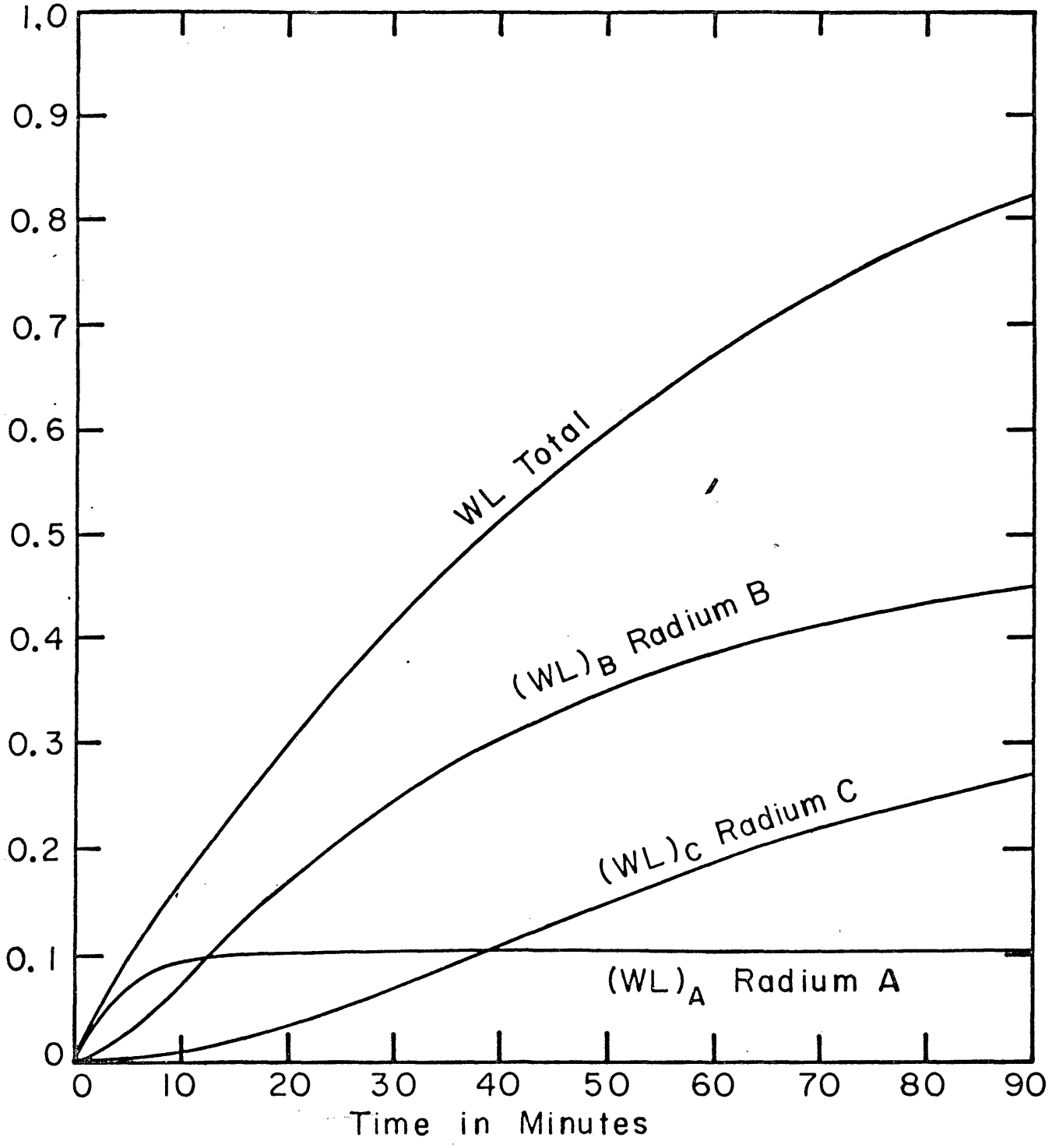


Figure 2. Growth of working levels in initially pure radon.

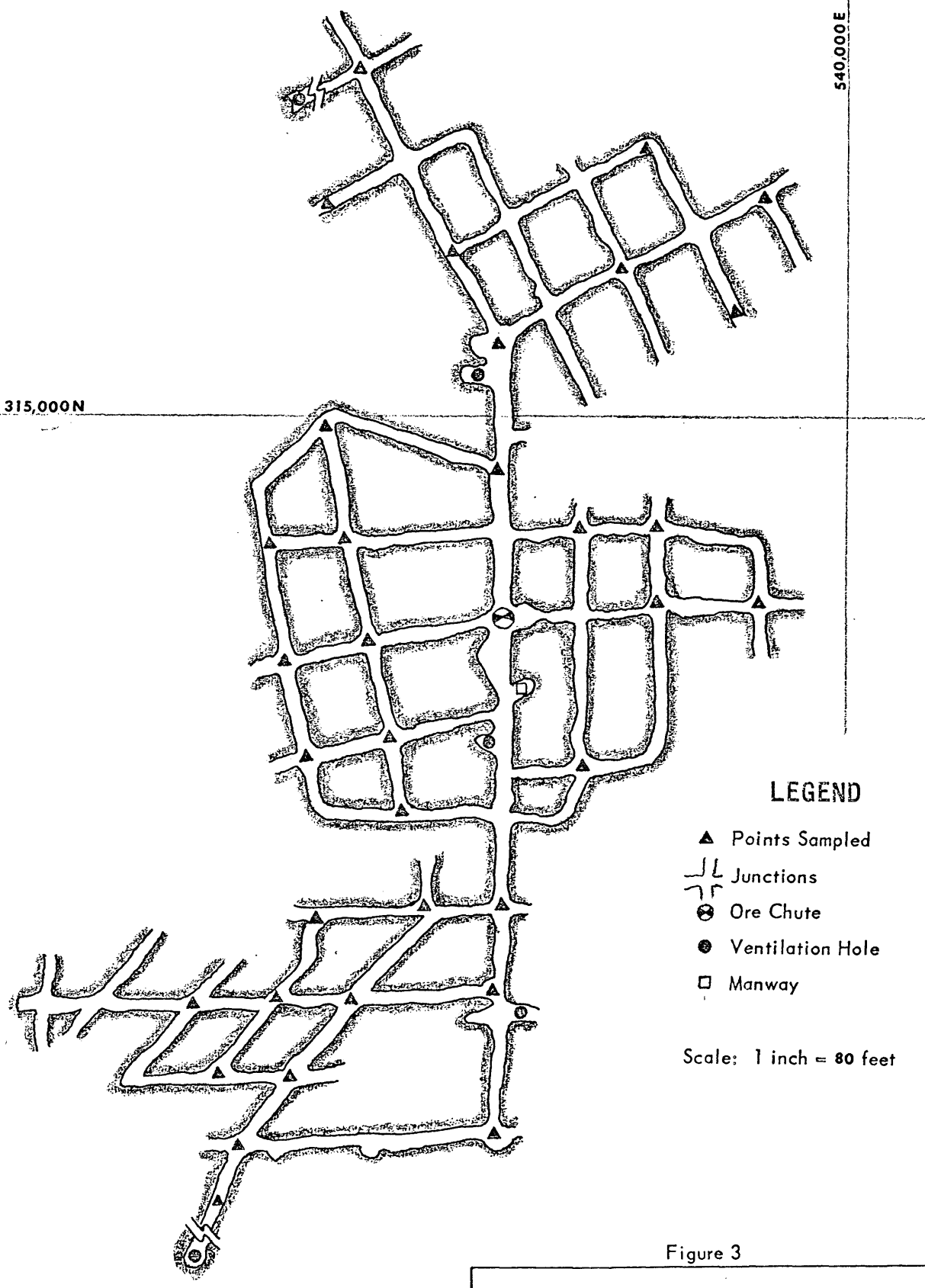


Figure 3

Rn222 and Radon Daughters Mine Survey	
Total Stope Area	November 1969

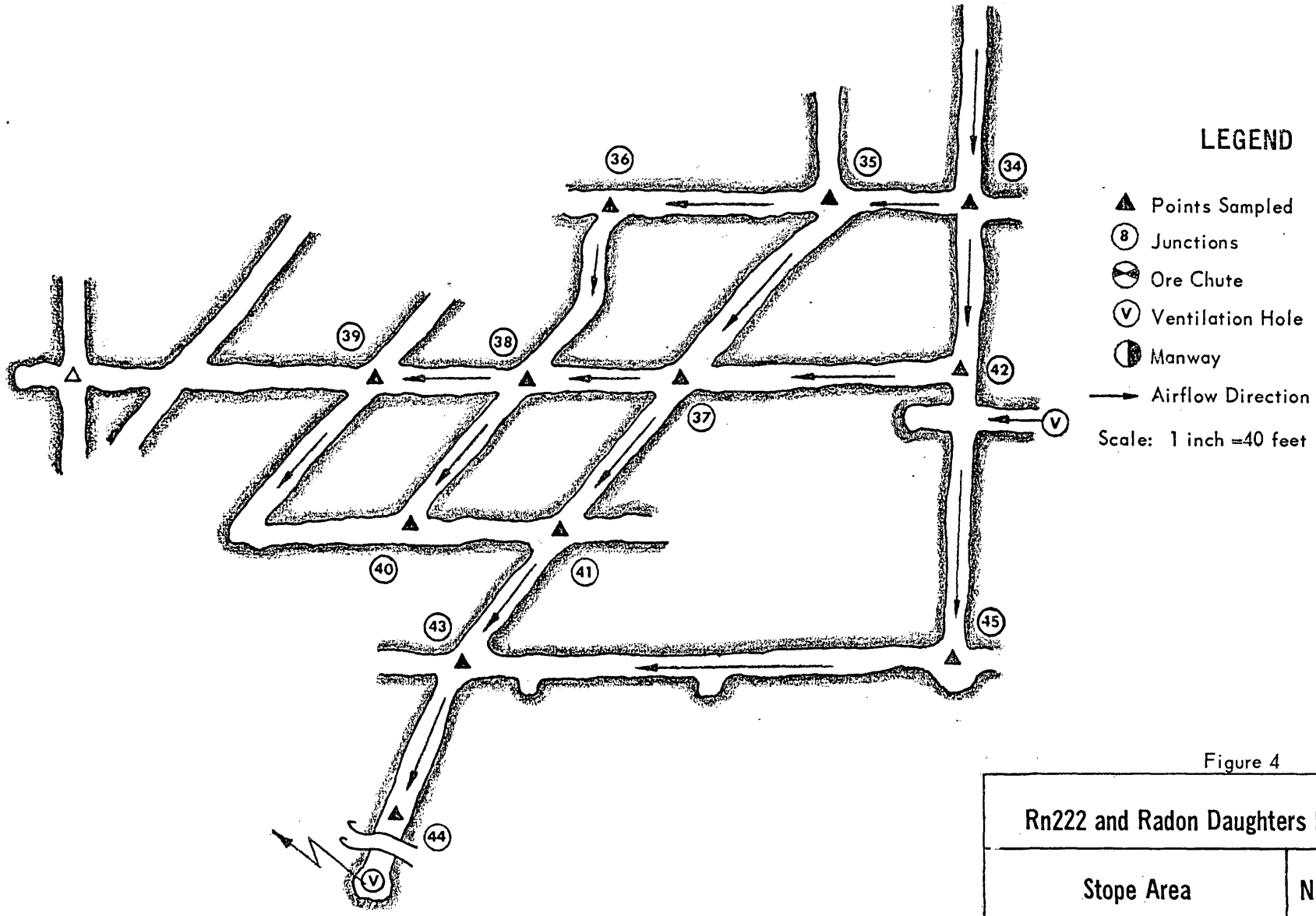
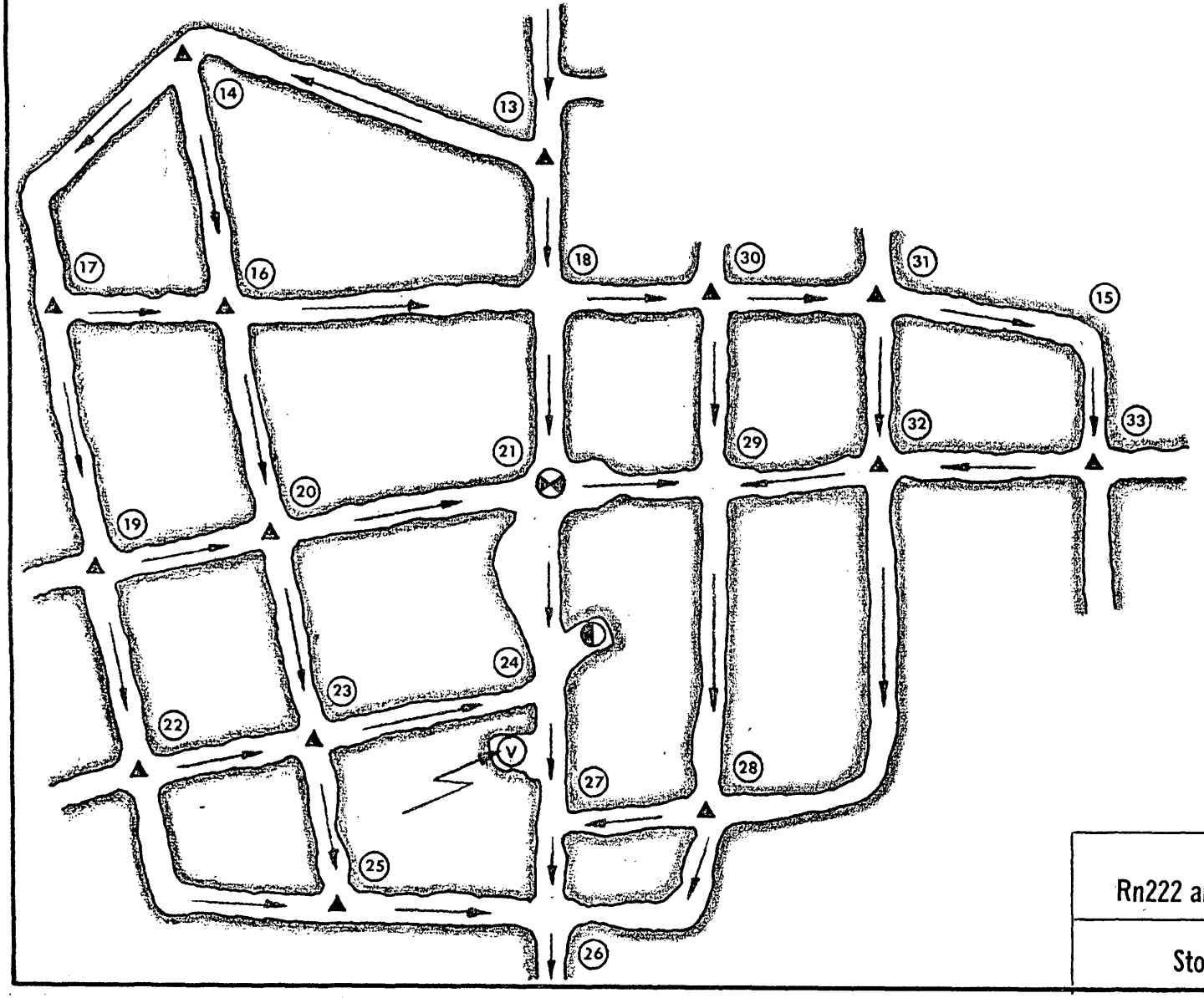


Figure 4

Rn222 and Radon Daughters Mine Survey	
Stope Area	November 1969



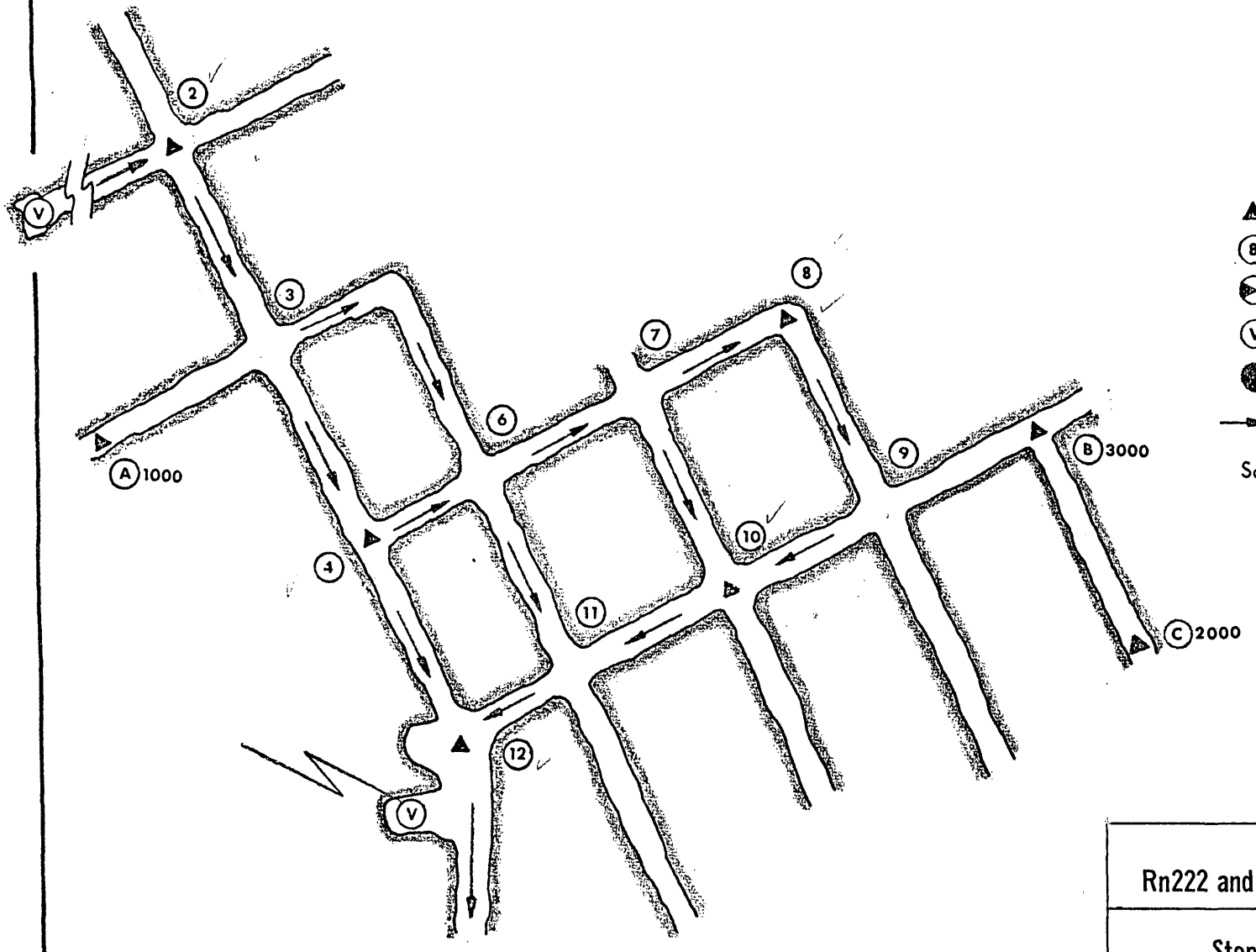
LEGEND

- Points Sampled
- 8 Junctions
- Ore Chute
- V Ventilation Hole
- Manway
- Airflow Direction

Scale: 1 inch = 40 feet

Figure 5

Rn222 and Radon Daughters Mine Survey	
Stope Area	November 1969



LEGEND

- Points Sampled
- (8) Junctions
- Ore Chute
- (V) Ventilation Hole
- Manway
- Airflow Direction

Scale: 1 inch = 40 feet

Figure 6

Rn222 and Radon Daughters Mine Survey	
Stope Area	November 1969

APPENDIX III

COMPUTER PROGRAM TO CALCULATE A VENTILATION NATURAL SPLITTING

```
C     ************************************************************************
C           SOLUTION OF A NATURAL SPLITTING PROBLEM IN URANIUM MINES
C     COLORADO SCHOOL OF MINES                                MINING DEPARTMENT
C     MN 701 GRADUATE MASTER THESIS                              YEAR 1969-70
C         JOSE A. LAMPAYA                                   THESIS NO. T 1285
C     LANGUAGE = FORTRAN IV                              COMPUTER = I C 4000
C     ************************************************************************
C
C                          P R O G R A M  N O .  1
C     MEANING OF THE MAIN VARIABLES USED IN THIS COMPUTER PROGRAM
C     ----------------------------------------------------------
C     E           LIMIT OF ACCURACY FOR ITERATION PROCEDURE, POSITIVE
C                 QUANTITY IN CFM
C     FF          FRICTION FACTOR OF THE BRANCH, 10**-10
C     H           HEAD LOSS IN THE BRANCH IN INCH OF WATER GAGE
C     HEIGHT      HEIGHT OF THE AIRWAY IN FEET
C     I           BRANCH IDENTIFICATION (NUMBER)
C     I           MESH NUMBER
C     IT          ITERATION NUMBER
C     J1-J2       FIRST AND SECOND JUNCTIONS OF A BRANCH RESPECTIVELY
C                 POSITIVE DIRECTION OF THE BRANCH IS FROM THE FIRST
C                 VALUE TO THE SECOND
C     L           NUMBER OF BRANCHES IN THE MESH
C     LENGTH      LENGTH OF THE AIRWAY(INCLUDING EQUIVALENT IN LENGTH)IN FEET
C     MAXOIT      MAXIMUM NUMBER OF ITERATIONS TO BE CARRIED OUT IFTHE
C                 SOLUTION DOES NOT CONVERGE
C     MAXIJ       HIGHEST NAMELY JUNCTION
C     NB          NUMBER OF BRANCHES OR AIRWAYS
C     NF          NUMBER OF FANS USED
C     NJ          NUMBER OF JUNCTIONS
C     NM          NUMBER OF MESHES
C     NS          NUMBER OF SAMPLE OF GAS AND DAUGHTER PRODUCTS TAKEN
C     PCI         MAXIMUN RADIATION CONCENTRATION IN PICOCURIES
C     Q           AIRFLOW IN THE BRANCH IN THOUSAND CFM
C     R           RESISTANCE OF THE AIRWAY
C     VE          AIR VELOCITY
```

```
C      WIDTH      WIDTH OF THE AIRWAY IN FEET                                    37
C      WL         WORKING LEVEL                                                  38
C      ******                                                                    39
       DOUBLE PRECISION ALPHA,AREA,BETA,BRANCH,C,D,DD,DH,DHF,DSQ,E,FF,FQ,       40
      1 FX,H,HEIGHT,HH,OUT,P,Q,R,RR,S,SIGMA2,SMALL,SUMD,SUMDH,SUMH,             41
      2 SUMNVP,T,TITLE,VE,W,WIDTH,X,Z,PCI                                       42
C      ******                                                                    43
       REAL NVP(550),LENGTH                                                     44
C      ******                                                                    45
       DIMENSION NA(1000),JC(500),BRANCH(70),R(70),Q(70),RR(70),MCI(70),        46
      1 OUT(70),J1(70),J2(70),ME(50),SUMNVP(50),ND(40),DD(80),WL(70),           47
      2 W(6),Z(6),S(6),C(40,6),P(7,20),FQ(40),HH(70),VE(70),AREA(70),           48
      3 JUNCT(50),EQUI(50),XMCI(50)                                             49
C      READ PARAMETERS AND DATA OF THE PROBLEM                                   50
    9  READ 499,NB,NJ,NS,MAXOJ,NF,MAXOIT,NBWNVP,NFIXB,E                          51
  499  FORMAT(8I9,F8.4)                                                          52
       IF(NB)10,10,11                                                           53
   10  STOP                                                                     54
   11  READ 500,(MCI(I),I=1,NS)                                                 55
  500  FORMAT(10I8)                                                             56
   12  READ 501,(WL(I),I=1,NS)                                                  57
  501  FORMAT(10F8.3)                                                           58
       READ 502,(JUNCT(I),I=1,NS)                                               59
  502  FORMAT(10I8)                                                             60
       NM=NB-NJ+1                                                               61
       NFBPF=NFIXB+NF                                                           62
       DO 15 I=1,NB                                                             63
       READ 503, J1(I),J2(I),R(I),FF,HEIGHT,WIDTH,LENGTH                        64
  503  FORMAT(2I10,5F10.2)                                                      65
       BRANCH(I)=I                                                              66
       IF(HEIGHT)14,14,13                                                       67
   13  AREA(I)=HEIGHT*WIDTH                                                     68
       R(I)=FF*(HEIGHT+WIDTH)*LENGTH/(2.6*AREA(I)*AREA(I)*AREA(I))              69
   14  RR(I)=R(I)                                                               70
   15  CONTINUE                                                                 71
C                                                                               72
```

```
C  ARRANGE BRANCHES IN DECREASING ORDER OF RESISTANCE                    73
      IS=NFBPF+1                                                        74
      IE=NB-1                                                           75
      JE=IE                                                             76
      L=0                                                               77
      DO 18 I=IS,IE                                                     78
      DO 17 J=IS,JE                                                     79
      IF(RR(J+1)-RR(J))17,17,16                                         80
   16 T=RR(J)                                                           81
      RR(J)=RR(J+1)                                                     82
      RR(J+1)=T                                                         83
      T=BRANCH(J)                                                       84
      BRANCH(J)=BRANCH(J+1)                                             85
      BRANCH(J+1)=T                                                     86
      L=1                                                               87
   17 CONTINUE                                                          88
      IF(L)19,19,18                                                     89
   18 JE=JE-1                                                           90
C                                                                       91
C  DETERMINE BASIC BRANCHES                                             92
   19 DO 20 I=1,MAXOJ                                                   93
   20 JC(I)=0                                                           94
      I=NB+1                                                            95
      L=0                                                               96
      N=0                                                               97
      DO 31 IJ=IS,NB                                                    98
      I=I-1                                                             99
      OUT(I)=0.                                                        100
      K=BRANCH(I)                                                      101
      JA=J1(K)                                                         102
      JB=J2(K)                                                         103
      IF(JC(JA)-JC(JB))26,28,21                                        104
   21 IF(JC(JB))22,25,22                                               105
   22 JJ=JC(JB)                                                        106
      DO 24 J=1,MAXOJ                                                  107
      IF(JC(J)-JJ)24,23,24                                             108
```

```
   23 JC(J)=JC(JA)                                                      109
   24 CONTINUE                                                          110
      GO TO 31                                                          111
   25 JC(JB)=JC(JA)                                                     112
      GO TO 31                                                          113
   26 IF(JC(JA))22,27,22                                                114
   27 JC(JA)=JC(JB)                                                     115
      GO TO 31                                                          116
   28 IF(JC(JA))29,30,29                                                117
   29 OUT(I)=1.                                                         118
      N=N+1                                                             119
      GO TO 31                                                          120
   30 L=L+1                                                             121
      JC(JA)=L                                                          122
      JC(JB)=L                                                          123
   31 CONTINUE                                                          124
      IF(N+NFBPF-NM)32,33,32                                            125
   32 CONTINUE                                                          126
   33 IF(NFBPF)36,36,34                                                 127
   34 DO 35 I=1,NFBPF                                                   128
   35 OUT(I)=1.                                                         129
C                                                                       130
C  FIND MESHES                                                          131
   36 JK=0                                                              132
      JE=0                                                              133
      L=0                                                               134
      DO 54 I=1,NB                                                      135
      IF(OUT(I))54,54,37                                                136
   37 K=BRANCH(I)                                                       137
      L=L+1                                                             138
      JK=JK+1                                                           139
      NA(JK)=K                                                          140
      JA=J1(K)                                                          141
      JB=J2(K)                                                          142
      N=I+1                                                             143
   38 DO 45 J=N,NB                                                      144
```

```
      IF(OUT(J))45,39,45                                                145
   39 K=BRANCH(J)                                                       146
      IF(JB-J1(K))41,40,41                                              147
   40 JB=J2(K)                                                          148
      JK=JK+1                                                           149
      NA(JK)=K                                                          150
      GO TO 43                                                          151
   41 IF(JB-J2(K))45,42,45                                              152
   42 JB=J1(K)                                                          153
      JK=JK+1                                                           154
      NA(JK)=-K                                                         155
   43 IF(JB-JA)44,51,44                                                 156
   44 OUT(J)=-1.                                                        157
      GO TO 50                                                          158
   45 CONTINUE                                                          159
      K=IABS(NA(JK))                                                    160
      IF(NA(JK))47,46,46                                                161
   46 JB=J1(K)                                                          162
      GO TO 48                                                          163
   47 JB=J2(K)                                                          164
   48 JK=JK-1                                                           165
      IF(JK-JE)49,49,38                                                 166
   49 K=BRANCH(I)                                                       167
      STOP                                                              168
   50 GO TO 38                                                          169
   51 DO 53 J=N,NB                                                      170
      IF(OUT(J))52,53,53                                                171
   52 OUT(J)=0.                                                         172
   53 CONTINUE                                                          173
      ME(L)=JK                                                          174
      JE=JK                                                             175
   54 CONTINUE                                                          176
      DO 55 I=1,NB                                                      177
   55 NVP(I)=0.                                                         178
      JE=0                                                              179
      DO 61 I=1,NM                                                      180
```

```
      JS=JE+1                                                          181
      JE=ME(I)                                                         182
      SUMNVP(I)=0.                                                     183
      DO 60 J=JS,JE                                                    184
      K=IABS(NA(J))                                                    185
      IF(NA(J))59,58,58                                                186
   58 SUMNVP(I)=SUMNVP(I)+NVP(K)                                       187
      GO TO 60                                                         188
   59 SUMNVP(I)=SUMNVP(I)-NVP(K)                                       189
   60 CONTINUE                                                         190
      L=JE-JS+1                                                        191
   61 CONTINUE                                                         192
  287 IE=NFBPF                                                         193
  288 READ 515, (DD(I),I=1,NFIXB)                                      194
  515 FORMAT(8F10.3)                                                   195
   89 DO 90 I=1,NB                                                     196
      Q(I)=0.                                                          197
   90 R(I)=R(I)*1.D-04                                                 198
      JE=0                                                             199
      DO 93 I=1,IE                                                     200
      JS=JE+1                                                          201
      JE=ME(I)                                                         202
      DO 93 J=JS,JE                                                    203
      K=IABS(NA(J))                                                    204
      IF(NA(J))92,91,91                                                205
   91 Q(K)=Q(K)+DD(I)                                                  206
      GO TO 93                                                         207
   92 Q(K)=Q(K)-DD(I)                                                  208
   93 CONTINUE                                                         209
C                                                                      210
C     COMPUTE Q VALUES                                                 211
      IB=NFIXB+1                                                       212
      DO 108 IT=1,MAXOIT                                               213
      IF(NFIXB)820,820,810                                             214
  810 JE=ME(NFIXB)                                                     215
      GO TO 830                                                        216
```

```
820 JE=0                                                                217
830 L=0                                                                 218
    SUMD=0                                                              219
    DO 107 I=IB,NM                                                      220
    IM=I-NFIXB                                                          221
    JS=JE+1                                                             222
    JE=ME(I)                                                            223
    SUMH=-SUMNVP(I)                                                     224
    SUMDH=0.                                                            225
    DHF=0.                                                              226
    IF(NFBPF-1)98,94,94                                                 227
 94 N=ND(IM)                                                            228
    FQ(IM)=C(IM,N+1)*Q(I)                                               229
    IF(N-1)97,97,95                                                     230
 95 J=N                                                                 231
    DO 96 IJ=2,N                                                        232
    FQ(IM)=(FQ(IM)+C(IM,J))*Q(I)                                        233
    DHF=(DHF+FLOAT(J)*C(IM,J+1))*Q(I)                                   234
 96 J=J-1                                                               235
 97 FQ(IM)=FQ(IM)+C(IM,1)                                               236
    SUMH=SUMH-FQ(IM)                                                    237
    DHF=DHF+C(IM,2)                                                     238
 98 DO 101 J=JS,JE                                                      239
    K=IABS(NA(J))                                                       240
    DH=R(K)*DABS(Q(K))                                                  241
    H=DH*Q(K)                                                           242
    SUMDH=SUMDH+DH                                                      243
    IF(NA(J))100,99,99                                                  244
 99 SUMH=SUMH+H                                                         245
    GO TO 101                                                           246
100 SUMH=SUMH-H                                                         247
101 CONTINUE                                                            248
    SUMDH=SUMDH+SUMDH-DHF                                               249
    IF(DABS(SUMDH)-1.D-20)106,106,102                                   250
102 D=-SUMH/SUMDH                                                       251
    DO 105 J=JS,JE                                                      252
```

```
      K=IABS(NA(J))                                                          253
      IF(NA(J))104,103,103                                                   254
  103 Q(K)=Q(K)+D                                                            255
      GO TO 105                                                              256
  104 Q(K)=Q(K)-D                                                            257
  105 CONTINUE                                                               258
      SUMD=SUMD+DABS(D)                                                      259
      IF(DABS(D)-E)107,107,106                                               260
  106 L=1                                                                    261
  107 CONTINUE                                                               262
      IF(L)109,109,108                                                       263
  108 CONTINUE                                                               264
      PRINT 519                                                              265
  519 FORMAT(10X,25H** D STILL GREATER THAN E)                               266
  109 CONTINUE                                                               267
      PRINT 520                                                              268
  520 FORMAT(1H1,25X,22HRADON DAUGHTERS SURVEY,//,16X,40HSECTION 33,1-5      269
     1LEVEL,STOPES AND HAULAGE,/,15X,42HSAMPLES TAKEN BY JOSE A. LAMPAYA     270
     2(NOV 1969))                                                            271
C                                                                            272
C     COMPUTE AND PRINT PRESSURE DROP AND AIR VELOCITIES FOR EACH AIRWAY     273
  110 PRINT 521                                                              274
  521 FORMAT(///14X,6HBRANCH,8X,2HJ1,3X,2HJ2,15X,1HR,15X,1HQ,15X,            275
     1 1HH,14X,2HVE/)                                                        276
      DO 111 I=1,NB                                                          277
      HH(I)=R(I)*DABS(Q(I))*Q(I)                                             278
      VE(I)=(DABS(Q(I))/AREA(I))*1000.                                       279
  111 PRINT 522,I,J1(I),J2(I),R(I),Q(I),HH(I),VE(I)                          280
  522 FORMAT(I20,5X,2I5,4PF16.6,0PF16.4,0PF16.7,0PF16.3)                     281
C                                                                            282
C     COMPUTE AND PRINT RADIATION LEVELS AND PERCENT OF EQUILIBRIUM          283
      PRINT 520                                                              284
      SUM=0.0                                                                285
      DO999 I=1,NS                                                           286
      XMCI(I)=MCI(I)                                                         287
      EQUI(I)=WL(I)*10000./XMCI(I)                                           288
```

```
      SUM=SUM+EQUI(I)                                                    289
  999 CONTINUE                                                           290
      AVE=SUM/FLOAT(NS)                                                  291
      PRINT 922                                                          292
  922 FORMAT(///35X,6HSAMPLE,5X,8HJUNCTION,5X,13HWORKING LEVEL,8X,5HPCI/ 293
     1L,4X,20HPER CENT EQUILIBRIUM/)                                     294
      PRINT 923,(I,JUNCT(I),WL(I),XNCI(I),EQUI(I),I=1,NS)                295
  923 FORMAT(I41,5X,I8,5X,F13.3,1X,F12.1,4X,F20.3)                       296
      PRINT 924,AVE                                                      297
  924 FORMAT(/////30X,54HTHE EQUILIBRIUM LEVEL OF RADON GAS IN SECTION 1 298
     1401 IS=,F8.3,8HPER CENT)                                           299
C                                                                        300
C  COMPUTE THE PRESURE TO BE ADJUSTED IN A FIXED QUANTITY BRANCH         301
C     R(I)*DABS(Q(I))*Q(I) IS ZERO IF R(I) OF A FIXED QUANTITY           302
C  -- BRANCH IS NOT GIVEN                                                303
      IF(NFIXB)880,880,850                                               304
  880 CONTINUE                                                           305
  850 PRINT 600                                                          306
  600 FORMAT(1H1,13X,49HHEAD LOSS TO BE ADJUSTED IN FIXED QUANTITY BRANCH,307
     1 ///14X,6HBRANCH,8X,2HJ1,3X,2HJ2,19X,1HR,19X,1HQ,16X,4HSUMH/)      308
      JE=0                                                               309
      DO 870 I=1,NFIXB                                                   310
      JS=JE+1                                                            311
      JE=ME(I)                                                           312
      SUMH=-SUMNVP(I)                                                    313
      DO 860 J=JS,JE                                                     314
      K=IABS(NA(J))                                                      315
      IF(NA(J))856,855,855                                               316
  855 SUMH=SUMH+HH(K)                                                    317
      GO TO 860                                                          318
  856 SUMH=SUMH-HH(K)                                                    319
  860 CONTINUE                                                           320
  870 PRINT 1522,I,J1(I),J2(I),R(I),Q(I),SUMH                            321
 1522 FORMAT(I20,5X,2I5,4PF20.6,0PF20.4,0PF20.7)                         322
      GO TO 9                                                            323
      END                                                                324
```

APPENDIX IV

NUMERICAL RESULTS

Table 10. Radon Gas Concentration.

Sample (Fig. 4)	TIME		ALPHA ACTIVITY (CPM)					Elapsed Time Minutes	Instrument Efficiency	Corrected Reading (Cpm)	Conversion Factor	pCi / Liter
	TT	TR	FR	SR	Σ	$\bar{x}=\frac{\Sigma}{6}$	Cpm / Liter					
34	10:58	15:57	158	164	322	53	841	299	.40	2102	0.1559	328
42	9:06	12:33	183	184	367	61	968	207	.40	2420	0.1541	373
37	9:12	12:42	184	181	365	61	968	210	.40	2420	0.1541	373
38	9:18	12:49	145	165	310	51	809	211	.40	2022	0.1541	311
39	9:26	12:55	165	159	324	54	857	209	.40	2142	0.1541	330
36	9:34	13:02	158	191	349	58	920	208	.40	2300	0.1540	354
35	9:41	13:09	234	211	445	74	1174	208	.40	2930	0.1540	451
41	9:50	13:15	138	157	295	49	777	205	.40	1942	0.1539	299
40	9:55	13:22	331	297	628	104	1650	207	.40	4125	0.1540	635
4000	10:02	13:32	389	430	819	136	2158	210	.40	5395	0.1541	831
43	10:15	13:39	187	200	387	64	1015	204	.40	2537	0.1539	390
45	10:20	13:51	309	279	588	98	1555	211	.40	3887	0.1541	599
5000	10:26	13:58	154	133	287	48	762	212	.40	1905	0.1541	293

Table 11. Radon Daughters Concentration.

Sample (Fig. 4)	TIME					ACTIVITY (CPM)			WL Factor	WL
	TT	TR_1	ETR_1	ETR_2	AVET	FR	SR	AVER		
34	11:07	13:56	169	171	170	34	33	34	0.01916	.668
42	9:10	11:12	122	124	123	84	123	103	0.00612	.630
37	9:16	11:17	121	123	122	87	98	93	0.00596	.554
38	9:22	11:22	120	122	121	87	79	83	0.00584	.485
39	9:30	11:28	118	120	119	167	160	163	0.00554	.903
36	9:38	11:33	115	117	116	111	129	120	0.00518	.622
35	9:46	11:38	112	114	113	109	121	115	0.00488	.561
41	9:53	11:43	110	112	111	159	147	153	0.00470	.719
40	10:00	11:51	111	113	112	320	306	313	0.00484	1.515
4000	10:08	11:56	108	110	109	392	379	385	0.00452	1.740
43	10:15	12:02	107	109	108	171	210	190	0.00442	.840
45	10:24	12:06	102	104	103	172	154	163	0.00400	.652
5000	10:31	12:11	100	102	101	228	226	227	0.00386	.876

Table 12. Radon Gas Concentration.

Sample (Fig. 5)	TIME		ALPHA ACTIVITY (CPM)					Elapsed Time Minutes	Instrument Efficiency	Corrected Reading (CPM)	Conversion Factor	pCi/Liter
	TT	TR	FR	SR	Σ	$\bar{X}=\frac{\Sigma}{6}$	Cpm/Liter					
13	9:18	2:08	137	113	250	41	650	290	.40	1625	0.1559	253
14	9:24	2:23	228	240	468	78	1237	299	.40	3092	0.1559	482
17	9:30	2:25	136	151	287	48	761	295	.40	1902	0.1559	296
19	9:36	2:36	230	216	446	74	1174	300	.40	2935	0.1559	457
22	9:45	2:43	178	175	353	58	920	298	.40	2300	0.1559	358
25	9:52	2:50	232	223	455	75	1190	298	.40	2975	0.1559	464
23	10:00	2:59	258	253	511	85	1348	299	.40	3370	0.1559	525
20	10:05	3:04	158	152	310	51	809	299	.40	2022	0.1559	315
16	10:12	3:11	191	154	345	57	904	299	.40	2260	0.1559	352
15	10:20	3:18	238	183	421	70	1110	298	.40	2775	0.1559	432
33	10:26	3:30	147	148	295	49	777	304	.40	1942	0.1559	303
31	10:33	3:37	172	187	359	60	952	304	.40	2380	0.1559	371
30	10:39	3:43	146	167	313	52	825	308	.40	2062	0.1560	322
29	10:46	3:47	46	51	97	16	254	301	.40	635	0.1559	98
28	10:54	3:50	149	158	307	51	809	296	.40	2022	0.1559	315

Table 13. Radon Daughters Concentration.

Sample (Fig. 5)	TIME					Activity (CPM)			WL Factor	WL
	TT	TR_1	ETR_1	ETR_2	AVET	FR	SR	AVER		
13	9:22	11:54	152	154	153	34	44	39	0.01244	.485
14	9:32	12:03	151	153	152	45	45	45	0.01210	.544
17	9:38	12:13	155	157	156	42	32	37	0.01352	.500
19	9:45	12:23	158	160	159	37	36	37	0.01438	.532
22	9:54	13:33	159	161	160	49	47	48	0.01484	.712
25	10:00	12:43	163	165	164	41	45	43	0.01642	.706
23	10:07	12:52	165	167	166	40	45	43	0.01736	.746
20	10:14	13:02	168	170	169	41	45	43	0.01878	.807
16	10:20	13:13	173	175	174	37	23	30	0.02138	.641
15	10:28	13:23	175	177	176	47	38	43	0.02300	.989
33	10:34	13:33	179	181	180	32	28	30	0.02556	.767
31	10:40	13:38	178	180	179	32	32	32	0.02486	.795
30	10:47	13:44	177	179	178	26	27	27	0.02420	.653
29	10:54	13:48	174	176	175	9	5	7	0.02242	.157
28	11:01	13:52	171	173	172	22	20	21	0.02000	.420

Table 14. Radon Gas Concentration.

Sample (Fig.)	TIME		ALPHA ACTIVITY (DPM)				CPM / Liter	Elapsed Time Minutes	Instrument Efficiency	Correct Reading (CPM)	Conv. Factor	pCi / Liter
	TT	TR	FR	SR	Σ	$\bar{X}=\frac{\Sigma}{6}$						
2	9:53	14:18	65	52	117	19	309	265	.40	773	0.1552	120
4	10:15	14:31	72	67	139	23	365	256	.40	912	0.1550	141
8	10:25	14:37	476	489	965	161	2557	252	.40	6392	0.1548	989
3000	10:32	14:43	2365	2315	4680	780	12378	251	.40	30946	0.1548	4790
11	9:10	14:01	502	559	1061	177	2809	291	.40	7025	0.1559	1095
1000	10:07	14:22	287	280	567	94	1491	255	.40	3729	0.1550	578
2000	10:40	14:52	2598	2402	5000	833	13220	252	.40	33049	0.1548	5116
121	10:55	15:01	280	292	572	95	1512	246	.40	3780	0.1548	585

Table 15. Radon Daughters Concentration.

Sample (Fig. 6)	T I M E					ACTIVITY (CPM)			WL FACTOR	WL
	TT	TR_1	ETR_1	ETR_2	AVET	FR	SR	AVER		
2	10:01	12:26	145	147	146	6	13	9.5	.01068	0.101
4	10:21	12:46	145	147	146	20	19	19.5	.01068	0.208
8	10:32	12:52	140	142	141	368	294	331	.00928	3.07
3000	10:39	12:58	139	141	140	1659	1567	1613	.00920	14.83
11	10:54	12:68	134	136	135	485	471	478	.00806	3.85
1000	10:12	12:42	150	152	151	31	46	38.5	.01178	0.453
2000	10:47	13:02	135	137	136	3493	3395	3444	.00820	28.24
12	11:01	13:12	131	133	132	91	90	90.5	.00754	0.682

Table 16. Numerical values, Mine Ventilation Network.

BRANCH	J1	J2	R	Q	H	VE
1	1	34	0.337437	12.4500	0.0052304	296.429
2	1	42	19.831731	6.0500	0.0725891	756.250
3	34	35	0.402619	6.4017	0.0016500	177.826
4	35	36	0.948006	2.7937	0.0007399	93.122
5	35	37	0.924501	3.6080	0.0012035	120.268
6	36	38	0.855556	2.7937	0.0006677	93.122
7	34	42	0.371180	6.0483	0.0013578	144.007
8	42	37	0.794357	4.3392	0.0014957	120.534
9	42	45	0.512904	7.7590	0.0030878	184.739
10	45	43	1.491994	7.7590	0.0089822	221.687
11	37	41	0.783476	5.7630	0.0026021	192.099
12	37	38	0.435264	2.1843	0.0002077	60.675
13	38	39	0.435264	2.0014	0.0001743	55.594
14	38	40	0.861823	2.9766	0.0007636	99.220
15	39	40	1.551282	2.0014	0.0006214	66.712
16	40	41	0.658120	4.9780	0.0016308	165.933
17	41	43	0.689459	10.7410	0.0079542	358.032
18	43	1	1.253561	18.5000	0.0429031	616.667

Table 17. Determination of percent equilibrium.

SAMPLE	JUNCTION	WORKING LEVEL	PCI/L	PER CENT EQUI.
1	34	0.668	328.0	20.366
2	42	0.630	373.0	16.890
3	37	0.554	373.0	14.853
4	38	0.485	311.0	15.595
5	39	0.903	330.0	27.364
6	36	0.622	354.0	17.571
7	35	0.561	451.0	12.439
8	41	0.719	299.0	24.047
9	40	1.515	635.0	23.858
10	4000	1.740	831.0	20.939
11	43	0.840	390.0	21.538
12	45	0.652	599.0	10.885
13	5000	0.876	293.0	29.898

Table 18. Numerical values, Mine Ventilation Network.

BRANCH	J1	J2	R	Q	H	VE
1	1	13	0.560145	8.4500	0.0039996	201.190
2	1	27	19.831731	4.0000	0.0317308	500.000
3	13	18	0.303693	5.3648	0.0008741	127.734
4	13	14	0.935818	3.0852	0.0006907	85.699
5	14	16	0.220433	1.9243	0.0000816	34.362
6	14	17	0.881633	1.1609	0.0001188	33.168
7	18	16	0.899933	0.9084	0.0000743	25.955
8	16	17	0.497331	0.8569	0.0000365	24.482
9	17	19	0.080932	2.0177	0.0000329	28.024
10	16	20	0.182818	1.9758	0.0000714	35.283
11	18	21	0.296944	2.1920	0.0001427	52.191
12	21	20	0.805203	-0.2479	-0.0000049	7.082
13	20	19	0.080932	-0.4806	-0.0000019	6.675
14	16	30	0.237555	2.2644	0.0001218	53.914
15	30	29	0.449966	0.8979	0.0000363	25.655
16	30	31	0.161209	1.3664	0.0000301	25.305
17	21	29	0.438125	0.6087	0.0000162	17.392
18	29	32	0.201381	-0.0669	-0.0000001	1.364
19	31	32	0.057319	1.1003	0.0000069	13.584
20	15	33	0.222708	0.2661	0.0000016	6.336
21	31	15	0.378604	0.2661	0.0000027	6.336
22	33	32	0.378604	0.2661	0.0000027	6.336
23	32	28	1.262267	1.2996	0.0002132	36.100
24	29	28	0.923615	1.5735	0.0002287	44.957
25	19	22	0.356333	1.5371	0.0000842	36.599
26	20	23	0.180683	2.2086	0.0000881	39.439
27	23	22	0.304368	-0.4369	-0.0000058	10.402
28	21	24	0.330688	1.8312	0.0001109	43.600
29	24	23	0.620252	-0.5663	-0.0000199	15.731
30	28	27	0.438125	0.0285	0.0000000	0.813
31	28	26	0.686791	2.8446	0.0005557	81.275
32	24	27	0.209211	2.3975	0.0001203	57.084
33	27	26	0.134975	6.4260	0.0005574	153.000
34	22	25	0.772594	1.1003	0.0000935	30.563
35	23	25	0.201381	2.0791	0.0000871	42.431
36	25	26	0.603902	3.1794	0.0006105	90.839
37	26	1	0.603902	12.4500	0.0093606	355.714

Table 19. Determination of percent equilibrium.

SAMPLE	JUNCTION	WORKING LEVEL	PCI/L	PER CENT EQUI.
1	13	0.485	253.0	19.170
2	14	0.544	482.0	11.286
3	17	0.500	296.0	16.892
4	19	0.532	457.0	11.641
5	22	0.712	358.0	19.888
6	25	0.706	464.0	15.216
7	23	0.746	525.0	14.210
8	20	0.807	315.0	25.619
9	16	0.641	352.0	18.210
10	32	0.989	432.0	22.894
11	33	0.767	303.0	25.314
12	31	0.795	371.0	21.429
13	30	0.653	322.0	20.280
14	29	0.157	98.0	16.020
15	28	0.420	315.0	13.333

Table 20. Numerical values, Mine Ventilation Network.

BRA CH	J1	J2	R	Q	H	VE
1	1	2	1.566952	4.8000	0.0036103	160.000
2	2	3	0.354308	4.8000	0.0008163	114.286
3	3	6	0.851733	1.8629	0.0002956	51.748
4	3	4	0.337437	2.9371	0.0002911	69.930
5	4	6	0.237555	0.4318	0.0000044	10.281
6	6	7	0.497331	1.0079	0.0000505	28.797
7	6	11	0.544080	1.2868	0.0000901	35.745
8	7	8	0.473649	0.4229	0.0000085	12.082
9	7	10	0.554962	0.5850	0.0000190	16.251
10	8	9	0.615743	0.4229	0.0000110	12.082
11	9	10	0.446146	0.4229	0.0000080	11.747
12	10	11	0.224943	1.0079	0.0000229	20.998
13	11	12	0.222708	2.2947	0.0001173	54.636
14	4	12	0.337437	2.5053	0.0002118	59.650
15	12	1	19.931731	4.8000	0.0456923	600.000

Table 21. Determination of percent equilibrium.

SAMPLE	JUNCTION	WORKING LEVEL	PCI/L	PER CENT EQUI.
1	2	0.101	120.0	8.417
2	4	0.208	141.0	14.752
3	8	3.070	989.0	31.041
4	3000	14.830	4790.0	30.960
5	10	3.850	1095.0	35.160
6	1000	0.453	578.0	7.837
7	2000	28.240	5116.0	55.199
8	12	0.682	585.0	11.658

APPENDIX V

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Alpha Particle: Charged particle, having a mass of four units and two unit positive charges of electricity, which is emitted from the nucleus of some atoms. It is composed of two neutrons and two protons.

Alpha Ray: Stream of fast-moving alpha particles. It is strongly ionizing and weakly penetrating radiation.

Beta Particle: Charged particle, having a mass and charge equal in magnitude to those of the electron, which is emitted from the nucleus of some atoms.

Beta Ray: Stream of high speed electrons of nuclear origin more penetrating but less ionizing than alpha rays; a stream of high speed electrons.

CFM: Cubic feet per minute.

Curie (c): Measure of quantity of radioactivity; one curie equals 2.22×10^{12} disintegrations per minute.

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.

Drift: A horizontal opening in or near an ore body and parallel to the course of the vein or long dimension of the ore body.

DPM: Disintegrations per minute. DPM equals number of atoms times decay constant.

Electron Volt: The amount of energy required to move one electron charge through a difference of potential of one volt. The unit is equal to 1.6×10^{-12} erg.

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

Gamma Ray: Electromagnetic radiation emitted from the nucleus of a radioactive atom.

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

in. w.g.: inches of the water gage.

MEV: Million electron volts of energy.

Picocurie (pCi): 1 x 10^{-12} curie; 222 disintegrations per minute.

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.

Radioactive Equilibrium: 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. (Radiological Health Handbook. Robert A. Taft, Sanitary Engineering Center, U.S. Public Health Service, Cincinnati, Ohio, 1952).

Radium A: Polonium218.

Radium B: Lead214.

Radium C: Bismuth214.

Radium C: Polonium214.

Radium D: Lead210.

Raise: A vertical or inclined opening driven upward from a level to connect with the level above, or to explore the ground for a limited distance above one level.

Stope: An excavation from which ore has been extracted.

LITERATURE CITED

Evans, R. D., and Kolenkow, R. J., 1968, Radium and mesothorium poisoning and dosimetry and instrumentation techniques in applied radioactivity -- Annual progress report: Massachusetts Institute Technology. Contract AT(30-1)952, part I, p. 335.

Joint Committee on Atomic Energy Congress of the United States (Ninetieth Congress) Hearings before the Subcommittee on Research Development and Radiation - First Session on Radiation Exposure of Uranium Miners, 1967, part 2, p. 40-42.

Kusnetz, H. L., 1956, Radon daughters in mine atmospheres: Indus. Hygiene Assoc. Quart., v. 17, p. 85.

SELECTED BIBLIOGRAPHY

Altshuler, B., Nelson, N., and Kuschner, M., Estimation of lung tissue dose from the inhalation of radon and daughters: Health Physics, v. 10, p. 1137-1161.

Bates, R. C., and Rock, R. L., 1962, Estimating daily exposures of underground uranium miners to airborne radon-daughter products: U.S. Bur. Mines Bull., Rept. Inv., no. 6106.

Cleveland, J. E., 1969, Uranium mine ventilation and employee exposure control: Am. Indus. Hygiene Conf., Denver, Colo.

Coleman, R. D., Kusnetz, H. L., Woolrich, P. F., and Holaday, D. A., 1956, Radon and radon daughter hazards in mine atmosphere: Indus. Hygiene Assoc. Quart., v. 17, p. 405-410.

Evans, R. D., and Kolenkow, R. J., 1968, Radium and meso-thorium poisoning and dosimetry and instrumentation techniques in applied radioactivity -- Annual progress report: Massachusetts Institute Technology. Contract AT(30-1)952, part I, p. 315-410.

Federal Radiation Council, 1967, Guidance for the control of radiation hazards in uranium mines: Tech. Rept., no. 8.

Glasstone, S., and Sesonske, A., 1963, Nuclear reactor engineering: Princeton, New Jersey, D. Van Nostrand Company, Inc., 830 p.

Goded, F., 1965, Teoria de reactores y elementos de ingenieria nuclear (Theory of reactors and elements of nuclear engineering): Spain, Publicaciones cientificas, Junta Energia Nuclear, 640 p.

Gotchy, R. L., 1968, A survey of bioassays for uranium miners -- Special Report U.S. Atomic Energy Commission Contract (11-1)1500. Colorado State Univ., Fort Collins, Colorado.

Hartman, H. L., 1961, Mine ventilation and air conditioning: New York, The Ronald Press Company, 398 p.

Holleman, D. F., 1968, Radiation dosimetry for the respiratory tract of uranium miners: Spec. Rept. U.S. Atomic Energy Comm., Contract AT(11-1)1500, Colorado State Univ., Fort Collins, Colorado.

Joint Committee on Atomic Energy Congress of the United States (Ninetieth Congress) Hearings before the Subcommittee on Research Development and Radiation - First Session on Radiation Exposure of Uranium Miners, 1967, part 2.

Kaplan, I., 1962, Fisica Nuclear (Nuclear Physics): Madrid, Aguilar, 728 p.

Kusnetz, H. L., 1956, Radon daughters in mine atmospheres: Indus. Hygiene Assoc. Quart., v. 17, p. 85-88.

Martz, D. E., 1968, Respiratory protection for uranium miners: Spec. Rept. U.S. Atomic Energy Comm., Contract AT(11-1)1500. Colorado State University, Fort Collins, Colorado.

McCurdy, D. E., 1969, Thermoluminiscent dosimetry for personal monitoring of uranium miners: Special Report on U.S. Atomic Energy Commission Contract AT(11-1)1500. Colorado State University, Fort Collins, Colorado.

Merril, E., and McDonald, E. W., 1969, Radioactivity studies: Prog. Rept., Inst. Environmental Medicine.

Palmer, H. E., Perkins, R. W., and Stuart, B. O., 1964, The distribution and deposition of radon daughters attached to dust particles in the respiratory system of humans exposed to uranium mine atmospheres: Health Physics, v. 10, p. 1129-1135.

Public Health Service, 1968, Guidelines to radiological health: Pub. no. 999-RH-33.

Thomas, J. W., 1968, Determination of radon progeny in air from alpha activity of air samples: New York, U.S. Atomic Energy Comm., Health and Safety Lab., 27 p.

Tsivoglow, E. C., and Ayer, H. E., 1964, Ventilation of uranium mines: Archives Industrial Hygiene and Occupational Medicine, v. 10, no. 5.

Van Dilla, M. A., and Taysum, D. H., 1955, Scintillation counter for assay of radon gas: Nucleonics, v. 13, no. 2, p. 68-69.

Wang, Y. G., and Hartman, H. L., 1967, Computer solution of three-dimensional mine ventilation networks with multiple fans and natural ventilation: Int. Jour. Rock Mech., v. 4, p. 129-154.

Westfield, J., Flinn, R. H., Look, A. D., and Morgis, G. G., 1968, Engineering control of health and safety hazards in uranium mines: U.S. Bur. Mines Bull. Inf. Circ., no. 7834.