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SOME PRACTICAL AND THEORETICAL CONSIDERATIONS OF PERSONAL ALPHA-PARTICLE DOSIMETRY

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FOREWORD

The material presented in this report deals with a subject of great practical interest, namely, personal α-particle dosimetry. The interested reader will no doubt ask the pertinent and crucial question: Why personal dosimetry and not, for instance, area monitoring? The answer to this question will become more apparent later on but a partial albeit authoritative answer to this question has been given by W. Jacobi in his address: "The New ICRP Recommendations on Occupational Limits for Radon Daughters" (International Conference on Radiation Hazards in Mining, Golden, Colorado, U.S.A., 1981). Jacobi said:

> ... the setting of reasonable limits solve only one part of the radon problem in mines. The experience in the past has shown, however, that the quality of the practical radiation protection in mines seems to be more essential for the level of safety. An improvement of monitoring, particularly of individual monitoring, and a careful planning, performance and surveillance of technical protection measures are necessary. We don't help the miners with a low limit if the practical application is insufficient. In this sense I think it is more sensible to get something done than reducing limits."

A topic of great concern in the field of radioactivity measuring techniques and radiation monitoring instrumentation is the confusing and often misleading terminology used. Specifically, the word 'dosimetry' is often referred to as the determination of exposure of airborne contaminants such as radon (and/or thoron) progeny. However, no instrument has ever been designed and built that measures the radiation arising from exposure to, say, radon progeny. What is actually measured by personal monitors is exposure. Hence, it is more adequate to refer to exposimetry, instead of dosimetry, when dealing with the time-integrated measurement of airborne radon (or thoron) progeny, and to exposimeter when refering to the actual function of the monitoring instrument used.

The present report deals with instruments (personal alpha exposimeters) that integrate, over time, the concentration of radon (thoron) gas or radon (thoron) progeny or of mixtures of radon and thoron gas, and/or of radon and thoron progeny for one of the two following purposes:

1. to determine the exposure to airborne radon and thoron progeny received by these workers _and, simultaneously_, to monitor air quality at the work place, or
2. to determine _only_ the exposure received by the workers, the monitoring of air quality at the work place being conducted by other means.

Furthermore, regulations in some countries require that exposures from every source of radiation (radon progeny, thoron progeny, airborne long-lived radioactive dust, and gamma radiation) be measured by personal, time-integrating instruments, while in other countries, only radon progeny monitoring is required.

Each specific objective will determine the specifications that a personal exposimeter must meet. Therefore, it is clear that the choice of a personal dosimeter must be based on the objective pursued, and of the intended use of the data obtained, and these vary from country to country, and possibly also from facility to facility.

In consequence, this report aims only at presenting the principles upon which the different instruments are based, and at indicating their strengths and shortcomings in regard to specific objectives or situations.

The goal of the authors is to inform the reader of the state-of-the-art in the domain of personal alpha exposimetry, and to guide the reader towards the system most adapted to his needs.

Although conceptually inappropriate, but in keeping with the conventional terminology, the terms dosimeter and dosimetry will be used throughout the text instead of the more correct terminology exposimeter and exposimetry, respectively, which reflect better the true nature of the instrument, and what it measures. We sincerely hope not to add to the confusion and further mislead the reader.

SOME PRACTICAL AND THEORETICAL CONSIDERATIONS OF PERSONAL ALPHA-PARTICLE DOSIMETRY

J. Bigu* and P. Duport**

ABSTRACT

The status of personal α-particle dosimetry in the uranium industry is presented. A brief description of personal dosimeters and prototypes is followed by some theoretical considerations regarding their practical use under steady-state and time-dependent field conditions. It is suggested that, at present, more effort should be placed on the evaluation of dosimeters than in the development of new ones. Also, more information should be gathered from countries which use personal α-particle dosimeters routinely. Furthermore, emphasis is recommended on comparison of personal dosimetry data with experimental data by area monitoring, using continuous monitoring systems, as well as with data by grab-sampling techniques.

Key words: Personal dosimetry: Alpha-particle dosimeters.

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INTRODUCTION

It has been recognized in recent years that the largest single contribution to the average effective dose equivalent received by the general public is from inhalation of radon progeny from natural sources (1).

In underground uranium mines and mills, miners and other personnel are exposed to three main radiation components: gamma radiation, radon progeny, and long-lived radioactive dust. Gamma radiation originates from external sources, e.g., mostly ^{214}Pb, ^{214}Bi and ^{226}Ra in mine walls. Radon progeny are found preferentially as airborne radioactive aerosols. Long-lived radioactive dust is found as airborne ore or as uranium concentrate. In some uranium mines, thorium is also present in the ore and personnel are exposed, in addition to the above radiation components, to thoron progeny and to thorium-laden airborne dust. Workers of non-uranium mines may also be exposed to high radon progeny concentration levels (2,3).

All the above forms of radiation pose serious potential health hazards to occupational workers. Characterization and quantification of the main radiation components in uranium mines, mills, and other uranium-related industries is a difficult task and a prime concern in occupational hygiene.

Personal dosimeters have been developed in an effort to estimate the exposure of workers to different kinds of radiation. A variety of personal α-particle dosimeters have been designed to determine the exposure of miners, and other personnel, to radon and thoron progenies in uranium mines and mills, as well as other uranium-related industries.

In spite of all the technical and practical problems associated with the design, performance and use of personal dosimeters, these instruments still provide, in principle, the most reliable method of estimating personnel radiation exposure.

Personal α-dosimeters are time integrating devices which are calibrated in terms of either α-particle radiation exposure, e.g., Working Level Month (WML) or Working Level Hour (WLH), or in terms of radiation level, i.e., Working Level (WL).

This report examines a number of topics of practical interest to the field of personal dosimetry. It also reviews the present status of personal dosimetry in uranium mines, and other uranium-related industries.

PERSONAL ALPHA-PARTICLE DOSIMETERS

Personal α-particle dosimeters are of two main types, namely, active dosimeters and passive dosimeters. The main differences between these two kinds of dosimeters are:

A. The use of a sampling pump and a filter, to collect decay products of radon and thoron, in the case of active dosimeters. This kind of dosimeter consists essentially of a servo-controlled sampling pump, a sampling head (housing an absolute filter), and an α-particle detector facing the active side of the filter, i.e., the side of the filter where air enters. Air flows through the filter where the short-lived decay products (progeny) of radon and thoron are deposited. Alpha-particles emitted by the α-particle emitters ^{218}Po(RaA), ^{214}Po(RaC'), and ^{212}Bi(ThC) and ^{212}Po(ThC') are detected by an appropriate detector.

B. The use of a membrane, porous material, or hydrophobic filter, in passive dosimeters. This type of instrument uses no pump or sampling filter. They generally consist of a sensitive volume housing a suitable detector. Radon and/or thoron diffuses passively through the membrane or porous material where the radon and thoron progeny are removed. Hence, only radon and/or thoron enter the sensitive volume, where they decay into their short-lived decay products, which are then detected by the α-particle detector.

Strictly speaking, these dosimeters can only estimate radon or thoron gas concentration. Radon progeny concentrations can only be estimated if the Working Level Ratio (WLR), also known as the F-equilibrium factor in the literature, is known. (The WLR, or F-factor, is defined as the ratio of the Working Level (WL) to the radon gas concentration, $[^{222}Rn]$, i.e., WLR = $(WL/[^{222}Rn]) \times 10^2$ where, $[^{222}Rn]$ is given in pCi/L. The square brackets are used to indicate concentration.) If the radon (thoron) progeny barrier is removed, the dosimeter reponds to both radon and thoron, and their progeny. Hence, assessment of radon and thoron progeny alone is very difficult. However, a combination of two dosimeters, one with the barrier, and the other without the barrier, placed side by side, permits an estimation of the radon and thoron progeny by subtracting the values obtained with the two independent dosimeters.

The type of α-particle detector which can be used in active and passive dosimeters is, in general, the same except on rare occasions. The detectors commonly used in personal α-dosimeters can be classifed as follows:

1. Detectors that require a somewhat elaborate form of chemical or physical processing in order to extract information, for example:
   i) TLD detectors such as LiF, CaF_2:Dy and $CaSO_4$:Tm (4-7);
   ii) Nuclear track-etch detectors such as cellulose nitrate (LR115), allyl diglycol carbonate (CR39), MAKROFOL E, and polycarbonates (8-12).
2. Solid-state electronic detectors such as silicon-barrier (SiB), diffused-junction (DJ), and Dynamic Random Access Memory (DRAM) detectors (13-17). Electrets can be classified somewhere between detectors of item 1 type and solid-state electronic detectors. Electrets operate by 'losing' their surface charge by α-particle bombardment from radon (thoron) progeny collected on a sampling filter (18).
3. Pseudo detectors, i.e., devices that are not by themselves true detectors,

but by forming part of some sort of mechanical structure, are used to collect radioisotopes on their surface by physical processes such as plate-out and thermophoresis (19). Metal or plastic discs are normally used for this purpose. Sometimes the collection efficiency of these devices is enhanced by electrostatic means. This is done either by applying a negative voltage to the discs, to collect positively charged radon and thoron progeny, or by using materials which are 'pre-charged', e.g., electrets (18). The discs are removed from the mechanical structure of the dosimeter and the radioactivity collected on their surface is measured with an α-particle counter using conventional techniques. Some passive dosimeters use activated carbon (C*) to adsorb radon gas which is gamma-counted. The gamma radiation detected comes mostly (~90%) from the decay of ^{214}Bi, which is one of the short-lived decay products of radon gas.

4. Detectors which do not belong to the three categories discussed above. Chemical dosimeters can be designed, in principle, in which the chemical reaction of, say, radon gas with a suitable chemical compound such as BrF_3 (20) could be used as a means to estimate radon gas concentration. Electrets can be used in a different fashion to that indicated in item 2. For instance, the ion-pairs produced in air by α-particles emitted by the radon and thoron progeny collected by a sampling pump/filter configuration, in an active dosimeter, can be detected by an electret. In this case, the loss of charge on the electret surface, caused by ion-pairs attracted to the electrically charged surface of the electret, can be used as a measure of the radioactivity collected on the filter (18). This radioactivity is in turn directly related to the airborne decay product concentrations.

Because passive dosimeters are inherently less sensitive and accurate than active dosimeters (21), electrostatic collection enhancement techniques are used sometimes.

In some cases, the dosimeters incorporate some sort of built-in counting system and memory unit, in which case the data can either be retrieved on command on the spot, or they can easily be transferred to an on-line computer, or any other communication network. Typical examples are solid-state electronic detector dosimeters such as those indicated in item 2. In most cases, however, some sort of physical or chemical manipulation of the detectors is required in order to retrieve the information (see items 1, 3 and 4).

From the above discussion it is clear that there is in principle a wide variety of dosimeters that could be developed in addition to the ones which are already available. Some concepts and/or dosimeters, however, present design problems, while others are, at present, only of academic interest.

PRACTICAL APPLICATIONS OF PERSONAL DOSIMETERS

The main purpose of a dosimeter is to provide a means to estimate personnel radiation exposure as accurately as practically possible. How well the dosimeter accomplishes this goal depends on a variety of factors. Furthermore, because the major health hazard associated with most uranium mines comes from the inhalation of radon and thoron progeny, it seems that in order to truly estimate personal radiation exposure, dosimeters should mimic the respiratory system in several respects. Also, because the response and behaviour of dosimeters to radiation depends on the type of instrument and technique used (see items A and B, and 1 to 4) dosimeters need to be calibrated in terms of meaningful radiation exposure units and under special exposure conditions.

It should be noted that personal exposure to radiation and radiation absorbed in tissue (as an index of biological harm) are two widely separated concepts. One of the reasons is that tissue exposure to inhaled radiation is determined by removal of radioisotopes by biological processes in addition to radioactive decay. Hence, a clear distinction should be made between radioactive half-life and biological half-life. Tissue damage is determined by the shorter of these two half-lives. With this in mind, the reader should be aware of the restricted role of personal dosimeters as a means of estimating the actual dose absorbed by tissue.

It has been pointed out that there are a number of requirements that a personal dosimeter should meet for optimal performance and as a realistic measure of radiation exposure. One of the requirements is for the dosimeter to mimic some characteristics or functions of the respiratory system. For instance, a conventional dosimeter of the active kind samples air at a constant flow rate whereas humans inhale air at a significantly different rate and frequency. These differences may limit the usefulness and accuracy of a dosimeter as an index of radiation exposure. The following discussion will illustrate the point in question.

Breathing is an intermittent although cyclic biological phenomenon. The respiratory frequency, tidal volume and minute volume (L/min) in adults varies with age, sex, individual, and level of physical activity and degree of stress, as illustrated in Table 1. The data on this table shows that the respiratory rate can vary from about 11 to 30 breaths/min, and the minute volume (i.e., respiratory airflow rate) from 4.5 to 43 L/min. Dosimeters usually operate, however, at sampling flow rates of about 0.1 L/min, i.e., more than one to two orders of magnitude lower. Furthermore, dosimeters supposedly operate at a constant airflow rate. It is important to note that if personal dosimeters of the active kind were to mimic the respiratory system, the filter would be exposed to rhythmic, although variable, pulses of radioactive aerosols. The growth and decay of these radioisotopes in the sampling filter would surely not be the same as for the case of constant airflow. To the knowledge of the author this very important point has not been investigated. Radiation exposure conditions as interpreted from personal dosimetry data may, therefore, differ substantially from actual exposure conditions.

Similar arguments could be used for passive dosimeters although the similarity with the functioning of the respiratory system is far less clear than for active dosimeters.

It is worthwhile noticing that although the radiation level at a working location may be maintained constant, and the dosimeter might or should also see it this way, the respiratory system sees and experiences a pulsating radiation field. Hence, in terms of accumulated radioactivity, the respiratory system will accumulate less than a dosimeter with the same flow rate. The difference between both depends on the breathing rate. Another important consideration is that while a dosimeter is continuously accumulating radioactivity on its filter, for humans, a fraction of the inhaled radioactivity is expelled during exhalation.

Furthermore, the problem is complicated by the fact that the risk due to exposure to airborne radioactive materials is estimated from two very different approaches. The first one is epidemiology of lung cancer among exposed populations. In this case, the observed health effect (lung cancer) is related to 'exposures', i.e., concentration of pollutant in air times duration of exposure. The second approach is dosimetry, in which the dose delivered to lung tissues is derived from a chain of parameters and events that include, in reverse sequence, the delivery of α-particle energy to individual cells, the deposition of radon daughter laden aerosol particles in the different segments of the respiratory tract, the size distribution and potential α-energy of aerosol particles, their concentration in the air, and breathing patterns of the exposed person.

Each of these two approaches require the measurement of different parameters in order to evaluate the risk to individuals. At present, only epidemiology provides us with a direct, albeit uncertain quantitative relationship between exposure and health effect. There are no practical means of determining, from physical measurements, the dose delivered to lung tissue by inhaled radon progeny, and to translate this into a quantitative risk value.

As a consequence, the only practical way of estimating individual risk due to exposure to radon progeny is through the determination of the exposure. Nevertheless, the measurement of aerosol size distribution, unattached fraction, and radioactive equilibrium factors are useful and necessary to refine dosimetric computations and to reduce the uncertainties attached to risk factors.

It should be noted that even a good knowledge of all the physical parameters that govern the penetration of aerosols in the respiratory tract, and the deposition of aerosol particles in the different segments of the bronchial tree and in the alveolar regions, would not be sufficient to forecast the health effects following the inhalation of radon progeny. Lung dosimetric calculations are currently limited by our relative ignorance of the types of cells that are more susceptible to changes leading to malignancy, and of the sensitivity of these cells to α-radiation. In other words, we do not know, with a good approximation, the response of bronchial epithelium cells to α-radiation. This ignorance is illustrated by the fact that researchers are still trying to determine whether the response of lung tissues to alpha, at low exposures, is linear, or infralinear, or supralinear. Additionally, unlike for other types of radiation and organs, we do not know whether there is a threshold below which exposure to radon progeny is totally harmless. The influence of co-carcinogens, initiating, or promoting agents acting in conjunction with α-radiation, is not very well known either.

Consequently, it seems prudent at this time, to concentrate on the accurate measurement of exposure, while gathering information on parameters that will allow further understanding of lung dosimetry. In the future, epidemiological studies improved by reliable exposure and death records, together with better knowledge of aerosol deposition and sensitivity of bronchial epithelium to α-radiation, and the influence of dose rate, will lead to the determination of more accurate risk factors.

DOSIMETER PERFORMANCE

There is little question that some types of dosimeters are more suitable for certain working environments than others. For instance, dosimeters which incorporate sophisticated electronics are more susceptible to failure and malfunction in dirty and hostile environments than 'mechanical' dosimeters, i.e., dosimeters with a minimum of electronics built into them, or no electronics at all.

The sensitivity of dosimeters which operate on electrostatic enhancement principles is humidity dependent. The use of these dosimeters is restricted to environments in which the air moisture content is known as a function of time so that adequate correction to the dosimeter data can be applied. A way of circumventing this drawback is by designing the dosimeter so moisture is kept out of the sensitive volume of the dosimeter.

Dosimeters of the active type, even those operated with servo-controlled pumps, exhibit airflow rate drifts in hostile environments, and suffer from relatively large power consumption problems. Passive dosimeters, on the other hand, are in general, less sensitive than active dosimeters.

Data retrieval from some dosimeters is quite easy. This feature enables data to be read on command providing a daily profile of radiation conditions in the working environment. Such is the case of solid-state electronic dosimeters. In other dosimeters, however, data retrieval is time consuming, cumbersome and delicate. Hence, data can only be retrieved on a periodic basis because of practical reasons. Examples of this type are dosimeters using TLD and nuclear track-etch detectors.

Dosimeters which are not very sensitive, although they may be very rugged, require long exposure times, thereby limiting the amount of information and data that can be obtained, and used, from them. However, the performance of a personal α-dosimeter should be judged against a major criterion: what use will be made of the reading? In fact, only two cases are possible. Either the readings of the dosimeter are used to determine individual exposures and for monitoring the quality of the ventilation network (in the case of underground mines, for example), or they are used only to determine individual exposures to radon progeny (and sometimes other radiation hazards as well). In the latter case, the monitoring of air quality at the work place is carried out independently from dosimetry functions.

The above are only a few considerations that the user should take into account in the application of personal dosimeters. The choice of one dosimeter type over another must then be based on a number of factors including long-term reliability, ruggedness, initial investment and routine maintenance, ease of operation and data processing and retrieval, as well as the separation, or no separation of dosimetry functions, from air quality monitoring.

The technical evaluation of, say, a personal dosimeter essentially consists of the following steps.

1. Calibration of the instrument under laboratory-controlled conditions. Working Level, decay product concentrations and disequilibrium ratios should be known. Similarly, aerosol concentration, aerosol size

distribution, and aerosol type, on one hand, and temperature, relative humidity, and airflow in the calibration facility should equally be known. In addition, testing should be carried out under different radiation, aerosol and environmental conditions.

2. Field evaluation of the dosimeter in, say, underground uranium mines to test its performance under adverse, hostile, environmental conditions.

Items 1 and 2 can be regarded as a technical performance test followed by an endurance performance test. No calibration of dosimeter is complete without these two phases of the evaluation.

Calibration work in test facilities is almost invariably conducted under constant conditions for the radiation level, and other relevant variables. However, this is hardly the case encountered in practice where radiation conditions and other environmental and meteorological conditions may vary considerably from day to day at a mine working location, or from location to location in a given day. Hence, as uranium mine workers, and other occupational workers in radioactive environments, operate under these variable conditions, dosimeters should also be evaluated taking these practical considerations into account.

A few considerations regarding the behaviour of dosimeters to constant and time-dependent radon (thoron) progeny conditions are discussed below.

A. TIME-INDEPENDENT CASE

The behaviour of active and passive dosimeters to radon and its progeny is somewhat different from that of thoron and its progeny. The different behaviour is related to the different radioactive half-lives of the radioisotopes involved.

It can be shown that the activity on the filter of a personal dosimeter of the active kind exposed to a radioactive atmosphere of constant concentration increases continuously until a constant, or equilibrium value is attained. This equilibrium is reached when the rate of radionuclides growth equals their radioactive decay rate. For radon progeny it takes about 4 hours for this equilibrium state to be reached. If the dosimeter is now suddenly removed from the radiation field it is not difficult to show that the activity of the filter decreases from its maximum value to a negligible value in about 4 hours.

The integrated activity during the 'ingrowth' sampling period (IAS), and during the decay or waiting period (IAW) are, in general, significantly different. Only for short sampling times, $T_s \lesssim 60$ min, IAW > IAS. In spite of these differences, however, these two quantities are complementary. This condition is expressed by the following equation:

$$\mathrm{IAS} + \mathrm{IAW} = (\mathrm{IAS})_{T1}^{T2} \qquad \text{Eq 1}$$

where, IAS is the integrated activity during a given sampling period between 0 and T_s;

IAW is the integrated activity during the waiting period T_w after the end of sampling, $T_w \gtrsim 240$ min. (This T_w is the time taken for total filter radioactive decay to occur.);

$(\mathrm{IAS})_{T1}^{T2}$ represents the integrated activity during a sampling period of the same length as IAS, but starting any time after activity equilibrium conditions in the sampling filter have been reached, i.e., 240 min (4 h) for radon progeny.

Equation 1 has been illustrated elsewhere (14, 15, 22, 27) for $T_s < 240$ min, $T_s = 240$ min, and $T_s > 240$ min, i.e., for sampling times less, equal and greater than the time necessary for radioactive equilibrium in the filter to be attained. Clearly,

$$\mathrm{IAS} < (\mathrm{IAS})_{T1}^{T2} = \int_0^{T_s} A_{eq.}\, dt \qquad \text{Eq 2}$$

where, $A_{eq.}$ is the equilibrium activity in the filter. What Equations 1 and 2 simply state is the following:

a) During the first 4 hours of the shift, the radon progeny activity collected either by an active (or passive) radon progeny dosimeter and the lungs of the worker gradually builds up until it reaches an equilibrium. At this point, under steady state conditins (constant concentration of radon progeny in the air), the additional activity of newly collected radon daughters is exactly compensated for by the decay of previously collected ones.

b) At the end of the shift, the radon progeny activity collected by the dosimeter and lungs of the worker gradually decreases, until all short-lived radon products have disintegrated into their corresponding long-lived radionuclides.

c) However, the activity integrated by the dosimeter during the period of time beginning with the shift, and ending with the complete decay of the radon progeny collected by the dosimeter, is representative of (proportional to) the quantity of radioactive decay that has taken place in the lungs of the worker. The same reasoning holds for thoron progeny, although the radioactive half-lives of thoron daughters are significantly different to those of radon daughters.

The reader is, of course, aware that the detector of an integrating personal dosimeter must not be disassembled from the source of radiation (filter, electrostatic collector, etc..) before all decay products have decayed. This waiting period is a minimum of 4 hours when radon progeny only are present, and 50 hours when thoron progeny are present.

The case for radon progeny is relatively straightforward because the time required for $A_{eq.}$ to be reached, and for the same to completely decay after the sampling period is much shorter than one working shift (~8 h). For thoron progeny the situation is more complicated as shown below.

For thoron progeny, equilibrium conditions in the sampling filter are never attained during a regular working shift. It can be shown that it takes $\lesssim$ 76 h for equilibrium to be reached under continuous, constant radiation exposure. Similarly, when the dosimeter is removed from the radiation field, the thoron progeny on the filter will decay for a long period of time, i.e., it takes again about 76 h for the activity on the filter to decay to 1% of the integrated activity during the first 240 min. Hence, the behaviour of the dosimeter for thoron progeny is unlike that for radon progeny. In summary,

i) Filter radioactive equilibrium conditions are never attained during a regular working shift;

ii) The decay of the activity accumulated in the filter during a sampling period (working shift) will continue beyond the end of the next shift. The contribution from radioactive decay between two consecutive, regular working shifts may amount to more than twice the activity accumulated during a regular working shift. The contribution from total radioactive decay (IAW) exceeds 4 times the integrated activity during a sampling period (shift), IAS.

It is clear from the above discussion that the contribution from radioactive decay after one shift will extend over several working shifts, although with decreasing 'strength' as the number of shifts increases. The situation becomes more complex after the dosimeter has been exposed for several working shifts. However, in spite of the above complexity the complementary principle stated by Equation 1 still holds for thoron progeny provided the filter be allowed to decay completely when removed from the radiation field.

The variables IAS and IAW depend on the progeny disequilibrium ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$ for the radon progeny, and $[^{212}Bi]/[^{212}Pb]$ for the thoron progeny, where the square brackets are used to indicate activity concentration. The above variables also depend on the sampling and waiting times.

Although passive dosimetry will not be dealt with here in detail, there are subtle differences between passive and active dosimeters of which the reader should be aware. Hence, the arguments for passive dosimeters differ from active dosimeters in a number of important points:

a) If the dosimeter uses a membrane, diffusion of radioactive gas is proportional to the gas concentration gradient between inside and outside the sensitive volume of the dosimeter. The operation of the dosimeter can be divided into two parts, namely, 'sampling' or direct diffusion in which radioactive gas diffuses into the sensitive volume of the dosimeter, and 'reverse' diffusion, i.e., the process whereby radioactive gas diffuses out of the sensitive volume of the dosimeter at an ever decreasing rate because of the decrease in gas concentration gradient. The radioactive gas in the sensitive volume decays into its progeny which reach a radioactive equilibrium with their parent after ~4 h for radon/radon progeny. In the reverse diffusion case, radioactive gas diffuses out of the sensitive volume at a rate proportional to the radioactive gas concentration gradient, as previously indicated. However, the decay products already formed cannot diffuse out and decay in the sensitive volume of the dosimeter. The radioactive gas remaining in the sensitive volume continues its decay until it diffuses out completely, or it decays completely first. Depending upon the permeability of the membrane and the radioisotope involved, the direct and reverse diffusion processes may not be complementary as for the active dosimeter case;

b) If no membrane is used, the response of the dosimeter depends on the F-value (e.g., $WL(Rn)/[^{222}Rn]$) and the radon (thoron) progeny flux, whereby the flux, J, is defined by the relationship $J = nv$. In this equation, n is the radon (thoron) progeny concentration, and v is the velocity of the particles. The variable v is obviously related to the airflow rate. Hence, it is possible to have widely different values for J with the same progeny concentration. This introduces difficulties in the interpretation of data obtained under varying airflow conditions.

A detailed study on the behaviour of passive dosimeters using membranes of different characteristics, e.g., permeability, has been published elsewhere (22-24).

It should be pointed out that passive dosimeters using membranes as decay products (progeny) barriers are almost exclusively intended for radon dosimetry purposes. Thoron is easily removed by membranes because its diffusion time is usually longer than its radioactive half-life (~55 s), unless the permeability of the membrane is very high.

Radon (thoron) progeny passive dosimetry using two dosimeters, one with a membrane (barrier) and the other without the barrier, placed side by side, is not very reproducible as well as very difficult to interpret because of items a) and b).

B. TIME-DEPENDENT CASE

Cases in which the radiation field is time-dependent are considerably more complex than cases under constant radiation field conditions. A number of cases have been examined such as sinusoidal, linear, exponential and step-wise perturbations, and how they affect the response and behaviour of active and passive dosimeters. The results of this study have been published elsewhere (22-24,26,27). The cases investigated are of great practical interest because field conditions rarely remain constant. Because each time-dependent case is different, generalizations are difficult, as the study in references 22-24, 26, and 27, clearly illustrate. In particular, it cannot be assumed that the dosimeter will react to arbitrary time-dependent radiation conditions occurring in practice by 'correctly' averaging the radiation field. How faithfully the dosimeter can provide an average field condition depends very much on the type of perturbation, the parameters which define the perturbation, the radioactive half-life of the radioisotopes involved, and the kind and characteristics of the dosimeter used.

COMPARISON AND CALIBRATION OF DOSIMETERS WITH GRAB-SAMPLING DATA

The assignation of individual exposures to radon progeny from grab-sampling monitoring data is accomplished by multiplying radon progeny concentrations expressed in WL units, by the time period during which the said concentration is assumed to be constant. This time period is determined administratively for a given work place. A worker generally goes to a number of work places during a dosimetry period (one month).

The accuracy and reliability of grab-sampling individual exposures depends on the variability of radon daughter concentrations at the work place. This variation can be large (25). The time recorded for each individual at each relevant work place is also subject to uncertainties, and for some categories of mine personnel (maintenance, first line management), the one-month period can be very large.

One obvious goal of personal dosimeters is to eliminate the sources of uncertainty in estimating personal radiation exposure, and to separate the function of air quality monitoring from those of dosimetry. This requires careful technical evaluation of the dosimeter. It is generally accepted that the following equation holds:

$$\int_{t1}^{t2} WL(t)dt = \Sigma_i (WL_{GS} \Delta t)_i \qquad \text{Eq 3}$$

where, WL(t) is the Working Level at time t, and t_2 and t_1 are the integration limits, i.e., the exposure, or sampling time, is t_2-t_1. In general, t_1 is taken as the reference time, hence, $t_1 = 0$. The symbol WL_{GS} stands for Working Level measured by grab-sampling methods, while Δt is the time interval during which an individual is exposed to a given Working Level (WL_{GS}). The left hand side of Equation 3 represents the integrating 'function' of the dosimeter, whereas the right hand side represents the discrete 'time-accumulated' Working Level as estimated by periodic grab-sampling measurements. It should be noted that continuous monitoring could be substituted for grab-sampling. However, this is not an established routine in calibration facilities, uranium mines or uranium mills. Apart from physical appearance and other more subtle details, continuous area monitoring devices suffer from the same disadvantages and share the same advantages as personal dosimeters.

If the technique suggested by Equation 3 is used to calibrate a dosimeter, tests should be conducted very carefully taking into account the theoretical and practical considerations discussed in previous sections.

Experimental data show that, in general, Equation 3 does not hold true. There are a number of reasons and combinations of factors which could explain the lack of agreement between dosimetry and grab-sampling data, such as:

1. Dosimeter sampling flow rate variations during a working shift and/or from working shift to working shift;
2. Long-lived radioactive dust contamination of the dosimeter sampling head;
3. Dosimeter radiation background contribution;
4. Overestimation of radon progeny Working Level, WL(Rn), due to thoron progeny contribution counted as radon progeny in dosimeters that do not discriminate between α-emitters;
5. Poor counting statistics of grab-samples, particularly at low Working Levels;

6. Plate-out of radon and thoron progenies in the dosimeter sampling head;
7. Alpha-particle absorption in the dosimeter sampling filter caused by dust loading;
8. Imprecise values for Δt, i.e., the worker's exposure time at a given location and radiation conditions;
9. Variations in radiation conditions from location to location and within a given location during a working shift.

Most of the above items affect the dosimeter response whereas, because of the short sampling time used in grab-sampling, only items 5 and 8 affect the right hand side of Equation 3.

The result of some long-term personal dosimetry programs in the Elliot Lake area shows that:

$$\int_{t1}^{t2} WL(t)dt < \Sigma_i (WL_{GS}\Delta t)_i \qquad \text{Eq 4}$$

The most likely candidates responsible for this systematic bias in the determination of radiation exposure by active dosimeters are items 6 and 7. Other factors should, of course, be taken into account as discussed in previous sections.

A seldom mentioned point in reports on comparison between grab-sampling and continuous time-integrating dosimeters is that some personal dosimeters may be intrinsically more accurate than grab-sampling techniques when measurements are conducted over long periods of time. Discrepancies between grab-sampling and time-integrating measurements should not always be interpreted as a deficiency of the concerned time-integrating device, unless the infallibility of the grab-sampling technique is demonstrated.

In the last few years, the development of personal dosimeters has advanced significantly. Dosimeters of the passive type have received greater attention than before in an effort to circumvent the shortcomings of active dosimeters, namely: flow-rate variations, power failure, and high power consumption.

Considerable effort, on the other hand, has been put into the design of low power, high efficiency, servo-controlled sampling pumps to minimize errors in exposure estimation arising from flow-rate variations, a characteristic of dosimeters of the active kind.

New, or improved, uses of diffused-junction detectors, electrets and DRAM chips, and better electronic circuitry design, have made certain types of dosimeters more flexible, versatile, and reliable under field conditions.

Laboratory evaluation of new dosimeter prototypes, and intercomparison of new prototypes with well established dosimeters in common use, has not yet been completed although a significant amount of work has been initiated at the Environmental Measurements Laboratory (EML), U.S.A., and the U.S. Bureau of Mines at the Denver Research Center (DRC), U.S.A., the National Radiological Protection Board (NRPB), U.K., the Australian Radiation Laboratory, (ARL), Australia, and the Elliot Lake Laboratory (CANMET), Canada (30-33,14-17). A great deal of work has also been done by several workers (34-37).

Field studies on the performance of personal α-particle dosimeters for uranium mine workers have been conducted in several countries such as Canada and the U.S.A. (4-7,38-43). The industrial application of α-particle dosimeters has been implemented by some countries (28,29,44). One country (France) has generalized the use of personal α-dosimeters to all its uranium miners. The instruments used provide monthly exposures to radon daughters, thoron daughters, long-lived dust and gamma-radiation (28,29). The same instrument is used in Niger to perform 'group' dosimetry. In this case, personal dosimeters are distributed to a fraction of workers of the same job category; the fraction depends on the dispersion of exposure measurements found for the said group during a preliminary survey of personal exposures.

CANMET has played a very substantial role in North America in the inhouse development and study of some dosimeter prototypes. in the development of other personal dosimeters under contract with private industry (16-17), and in the technical evaluation of all available dosimeters, at the time, under laboratory-controlled conditions in a radon/thoron test facility (RTTF), and in several underground uranium mines. The results of these studies have been reported elsewhere (14,15,41).

The AECB has provided substantial funding and expertise over the years to universities, private industry, and other government agencies to carry out special studies on personal α-particle dosimetry.

However, to the knowledge of the author, little or no work is currently being done in the following relevant areas:

1. Response of dosimeters under time-dependent radiation level conditions;
2. Behaviour of dosimeters in thoron/thoron progeny atmospheres, and in arbitrary mixtures of radon, thoron and their progenies;
3. Performance of dosimeters in radioactive atmospheres containing long-lived radioactive dust (LLRD), known to severely contaminate the sampling heads of some dosimeters;
4. Technical evaluation of new dosimeter prototypes, and intercomparison of new prototypes with dosimeters in common use, in underground uranium mines and uranium mills.

A number of considerations should be borne in mind to assess the extent of the errors incurred in estimating radiation levels when average values, or 'instantaneous' values, such as those obtained by grab-sampling techniques, for the radiation level are assumed as representative of actual time-dependent radiation field conditions (see item 1). Some of the factors that have a bearing on the subject are the following:

1. sampling time (exposure) time;
2. radioactive species under consideration, i.e., half-life;

3. radiation field conditions, i.e., constant or time-dependent:
4. type of time-dependent radiation condition, e.g., linear, step-wise, sinusoidal, exponential, or a combination of two or more of the above.

CONCLUSIONS

There is a variety of personal α-particle dosimeters available. Some of the dosimeters have been in operation for a long time. However, other dosimeters are relatively new and in the prototype state. They are under technical evaluation.

The choice of one dosimeter over another must be based on a number of factors such as specific application and type of environment where the dosimeter is to be used, long-term reliability, ruggedness, sensitivity, initial investment and routine maintenance, man-power consumption, ease of operation, and ease of data processing and data retrieval. In spite of the obvious benefit of α-particle dosimeters for personal radiation exposure purposes, their use is not widespread, there being only a few uranium mines where the dosimeters are employed on a routine basis.

The field of personal dosimetry should be carefully reexamined in the light of past experience, and the advent of new and more reliable technology. The above discussion suggests that there is still a great deal to be done regarding the laboratory and field evaluation of personal dosimeters, and in the intercomparison of dosimeters used at present on a regular basis and new prototypes. Canadian field conditions are unique in some regards, and the conditions under which the dosimeters are evaluated should reflect this fact.

It is suggested that, at present, more effort should be placed on the evaluation of dosimeters than in the development of new ones. Also, more information should be gathered from countries which use personal α-particle dosimeters routinely. Furthermore, emphasis is recommended on comparison of personal dosimetry data with experimental data by area monitoring, using continuous monitoring systems, as well as with data by grab-sampling techniques.

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Table 1 - Respiratory frequency, tidal volume, and minute volume for adults.

Sex	Body Weight (kg)	Conditions	RF (breaths/min)	TV (L)	MV (L/min)
Male	68.5	Rest	11.7(10.1-13.1)	0.75(0.575-0.895)	7.43(5.8-10.3)
		Light work	17.1(15.7-18.2)	1.673(1.51-1.77)	28.6(27.3-30.9)
		Heavy work	21.2(18.6-23.3)	2.03(1.9-2.11)	42.9(39.3-45.2)
Female	54.0	Rest	11.7(10.4-13.0)	0.339(0.285-0.393)	4.5(4.0-5.1)
		Light work	19	0.86(0.836-0.885)	16.3(15.9-16.8)
		Heavy work	30.0(25.0-35.3)	0.88(0.49-1.27)	24.5(17.3-31.8)

Notes: RF, TV, and MV stand, respectively, for respiratory frequency, tidal volume, and minute volume. Figures in round brackets indicate range of values measured experimentally. The values outside the round brackets represent average (mean) values.

Data taken from Biological Data Book, vol. III, 2nd Edition, P.L. Altman and D.S. Dittman (Eds.), Federation of American Societies for Experimental Biology, Bethesda (MD , U.S.A), 1974.