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RADON DAUGHTER EXPOSURE ESTIMATION AND ITS RELATION TO THE EXPOSURE LIMIT

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PAPER

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This paper was submitted to the International Conference on Radiation Hazards in Mining: Control, Measurement and Medical Aspects, Golden, Colorado, U.S.A., October 4-9, 1981.

ABSTRACT

Under current Atomic Energy Control Regulations, the annual limit for individual exposure to radon daughters is 4 WLM. The Regulations do not specify how the exposure is to be determined nor to what accuracy the measurements should be made. This paper discusses the historical and conventional grab-sampling and time-weighting methods for assigning exposures to radon daughters in uranium mines in Canada. As a further step in the evolution of exposure assignments, the system of personal radon daughter dosimetry is introduced as the more accurate means of assigning individual exposures and of adhering to the intent of the exposure limit.

RÉSUMÉ

En vertu du Règlement sur le contrôle de l'énergie atomique, la limite annuelle de l'exposition d'un particulier aux produits de filiation du radon est de 4 WLM. Le Règlement ne précise pas la façon de déterminer l'exposition ni le degré de précision des mesures. Le présent document fait état des méthodes passées et classiques d'échantillonnage par grappillage et de pondération temporelle pour établir des taux d'exposition aux produits de filiation du radon dans les mines d'uranium du Canada. Comme nouvelle étape dans l'évolution de l'établissement des taux d'exposition, on a mis en oeuvre un système par lequel des dosimètres individuels seront utilisés afin de mesurer avec plus de précision les doses absorbées par les particuliers et de permettre le respect des limites d'exposition.

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INTRODUCTION

This presentation is concerned with the administrative and technical capability of the Atomic Energy Control Board (AECB) to assure compliance with the individual exposure limit for radon daughters (currently 4 WLM per year). It is not concerned with the epidemiological bases for setting the exposure limit. Moreover, the intent is to show how sophisticated methodologies and advanced technologies, applied to radon daughter concentration measurements in uranium mines, convey the spirit of compliance by providing better estimates than do the historical methods. These better estimates mean that more accurate and more precise estimates of each worker's exposure are determined using these more modern methods and devices. The estimates so derived should provide more convincing evidence to an individual worker that his assigned exposure is a valid indicator of his true exposure. In addition, a perspective on the exposure estimate in relation to the exposure limit is given as further evidence that an exposure limit is not the dividing line between "safe" and "unsafe" exposures.

A brief description is given of the compliance aspects of the Atomic Energy Control Regulations and of the limitations of purely statistical non-compliance procedures. Most of the emphasis of the paper will be placed on the uncertainties associated with conventional radon daughter exposure determination and the means being employed (and anticipated) to reduce these uncertainties.

NON-COMPLIANCE

Under current Atomic Energy Control Regulations (1978), the annual individual exposure limit for radon daughters is given without reference to the possible methods of sampling and calculation of radon daughter exposure and without any reference to possible uncertainties or their magnitudes. This is common in such statutes, the details of sampling, calculation, error analysis, and so on, being left for licence conditions or provided as a specific guideline to the licensee on the matter of compliance with the Regulation. Since the exposure limit is contained in the Regulations, compliance with it is absolute, as with any other law.

In Canada, a state of non-compliance with the radon daughter exposure limit exists when an exposure (attributed to an employee) is reported by the licensee to exceed the limit. No uncertainty in the measurements or in the overall determination of exposure is reported nor is any requested. Removal of the worker and the loss of his services are the immediate and direct penalty suffered by the licensee for failure to maintain the exposure at, or below, the limit. A worker may be re-instated to employment for the balance of the reporting period only if the licensee can assure the AECB that further significant exposure to the worker will not ensue.

In other jurisdictions, such as the United States, non-compliance is defined on a statistical basis. For example, NIOSH, the National Institute for Occupational Safety and Health presents procedures for calculating the 95% Lower Confidence Limit (LCL) in order to "compare the results of occupational environmental sampling to an occupational health standard and make a decision with a known chance of making an incorrect decision that a state of non-compliance exists" (Leidel and Busch, 1975). (In the nomenclature of this presentation, exposure limit would be used in place of "standard", in the NIOSH sense). Furthermore, it is emphasized in the NIOSH document that such numerical comparisons "are necessary only if the sample mean is greater than the standard". The NIOSH document points out, quite correctly, that the "statistical procedures presented below will not detect and do not allow for analysis of highly inaccurate results, i.e., systematic (non-random) errors or mistakes...If a systematic error is known to exist in an instrument or analytical procedure then correct the sample mean of the data before analyzing for non-compliance".

It is certainly not the purpose of this paper to criticize the sophisticated statistical approach to non-compliance as given in the NIOSH document or in similar approaches used in other jurisdictions. Rather, the purpose is to approach, with some introspection, the question of the determination of exposure by the employer for his employee and especially the employee's understanding of, and confidence in, the accuracy of the exposure determination and its relation to the exposure limit.

DETERMINATION OF EXPOSURE

Historically, in uranium mines, exposure to radon daughters for an individual miner was determined by some combination of measurements (or estimates) of concentration of radon daughters weighted by estimates of the time spent in locations by that individual where those concentrations were measured (or estimated). Several major (and sometimes questionable) assumptions have had to be made both with respect to the concentrations and to the occupancy time attributed to these concentrations. The assumptions concerning the concentrations dealt with their constancy in time and space, the accuracy and precision of the method of measurement, the appropriateness of applying these concentrations to workers in the same general work area but performing different types of work, and the inclusion of thoron daughters. Concerning time, the assumptions depended heavily on a worker's reporting of his own (or another's) time spent in various work locations and, to a lesser extent, in travelways, lunch room and so on.

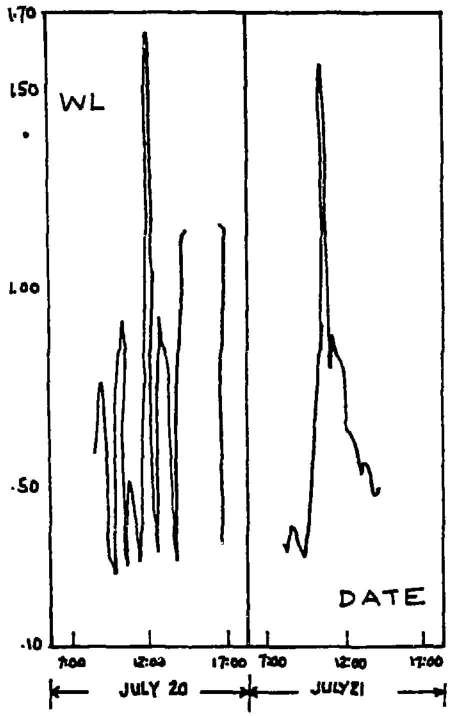

FIGURE 1. Radon daughter concentrations measured by grab sampling in one location in a Canadian uranium mine over two days. (Adapted from Makepeace and Stocker, 1980).

It goes without saying that the variations in concentrations of radon daughters in operating mines are large (by an order of magnitude or more) from one location to another and even at a given location. These variations are strong functions of the ventilation rates and the effectiveness of the ventilation design, the physical actions of drilling, breaking and hauling ore (i.e., the type of mining), and pressurization of the mine. The inhalation and retention parameters for a miner breathing the mine air are determined further by the amount of dust (and whether dust suppression techniques are used), humidity, condensation nuclei concentration (including diesel particulates), the charge state of the radioactive ions produced, and the extent and vigour of his own physical activities.

An example of such variation is shown in Fig. 1 (Makepeace and Stocker, 1980). In this example, fan failure accounts for the largest excursions, giving rise to even further variations in local concentrations.

As for the accuracy and precision of the concentration measurements, numerous studies have dealt with the inherent inaccuracies of various grab-sampling methods in common use (such as the Kusnetz and Rolle methods) to say nothing of the systematic inaccuracies associated with inappropriate sampling times, improper handling and counting of the filters and so on.

Another study (Yourt, 1978) has shown that men working in the same general work area actually can be exposed to different concentrations of radon daughters depending on the kinds of work that each is performing including the amount of comminution and the presence or absence of dust suppression measures.

While, historically, thoron daughter concentrations have tended to be included in whatever radon daughter concentration measurements were being made, in fact, an uncertainty, comparable in magnitude to those above, may be introduced because of the relative amounts of thoron daughters and radon daughters present. Recent measurements (Tremblay et al., 1980; Bigu et al., 1981) have shown that, in the Elliot Lake mines, comparable amounts of radon daughters and thoron daughters may be present at any given time or location because the host rock contains both uranium and thorium ore.

It is also well known that accurate time keeping in underground mines is not always achieved and the assignment of these times to particular concentrations carries with it the same uncertainty to the exposure estimation. It is, in fact, often suggested that the uncertainties associated with time keeping and time assignment to specific tasks (through time and motion studies) are larger than the uncertainties associated with the determination of radon daughter concentrations.

ACCURACY

The preceding section illustrates how a variety of assumptions may lead to gross (systematic) errors in the determination and consequent reporting of exposures attributed to individuals. These assumptions, coupled with sampling, measurement and calibration errors and errors in the assignment of time to particular concentrations can contribute to a very inaccurate estimate of a worker's actual exposure.

While assumptions continue to play a significant part of any system of estimation based on grab sampling and time weighting, the advances in technology, in good industrial practice and in improved control of the workplace environment, have contributed to a situation such that exposures in excess of 4 WLM per year are rare at present. Moreover, the average of all exposures in recent years is of the order of 20% - 40% of the exposure limit.

PRECISION

The preceding section on systematic uncertainties shows that significant doubt may exist in the estimation and reporting of a worker's personal exposure. With respect to the exposure limit, the reported exposure for an individual may actually be one of the following cases (and shown schematically in Fig. 2).

Cases (a) and (d) are the most clear cut since the uncertainties (confidence limits) are completely within the exposure limit (case (a)), or outside of it (case (d)).

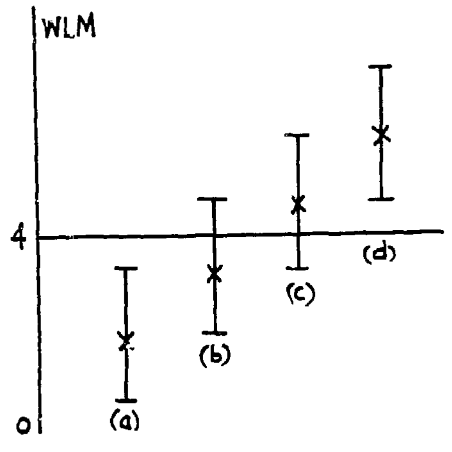

FIGURE 2. Examples of reported exposures with uncertainties assigned.

Cases (b) and (c), however, are more important for this discussion and are more difficult to deal with. All other things being equal, an exposure represented by case (b) would be considered to be in compliance (in Canada) whereas case (c) would not be. In cases (b) and (c), the distance between the lower error bar (or Lower Confidence Limit in the NIOSH nomenclature) and the exposure limit is a measure of the reliability that the mean value (of a large number of individual samples) is at, or below, the exposure limit. In these cases, one is dealing with the more nebulous concepts of probabilities and likelihoods and the situation is less well defined. (Concepts such as "safe" and "unsafe" exposures clearly lose any remnant of significance in these instances). Since the uncertainties are not reported, no credit (for compliance) can be given by the AECB in situations such as case (c). Moreover, since the uncertainties represented by the error bars are, in practical situations, the composites of the random (statistical) and non-random (systematic) errors, it is not a trivial matter to separate these errors and apply statistical tests alone to determine non-compliance.

It should be pointed out that these approaches do not address each and every aspect contributing to the uncertainty of exposure estimation. Rather they are the beginnings of deliberate attempts to identify the non-random and random elements of the estimation. Some of the initiatives have been underway for short times; others are under staff investigation, while still others (such as more accurate time accounting) have been addressed in terms of the AECB auditing programs to identify time-accounting errors.

Two independent approaches are underway, currently. One deals with minimizing the uncertainties from the grab-sampling and time-weighting method, while the second deals with the development of reliable personal radon daughter dosimeters. While certain actions have been taken recently by the AECB with respect to the imposition on the mining companies of limited personal dosimetry, both approaches will be described with greater emphasis being placed on the introduction and use of personal dosimeters.

REDUCTION OF NON-RANDOM AND RANDOM ERRORS

The approaches by the Atomic Energy Control Board with respect to reduction of error in the determination of radon daughter exposure can be divided into the non-random and random aspects.

Non-random

Guidelines have been issued (1981) to the uranium mining companies with respect to standardizing the methods of sampling by the Kusnetz method. These guidelines specify the details of calibration, sampling period, counting of filters, calculation of concentration and so on. Consideration was also given to a requirement to assure that the individual exposure be given with an "error" no larger than 50% at the 95% confidence level, in the sense given in the ANSI standard (ANSI, 1973). Problems in the implementation of such a requirement, for each individual worker, caused this approach to be withdrawn. (There is some hope that the "error" so defined can be reduced when more experience is acquired by the companies in the standard sampling and measuring techniques and when the non-random errors can be identified).

Random

The attempt to reduce the random portion of the error centres on the use of a stratified random sampling plan (Makepeace and Stocker, 1980; Makepeace and Stocker, 1980a; Makepeace, 1981). Grab sampling is carried out using a scheme based on randomization which ensures that each location, occupation and time of sampling has equal opportunity of being selected without bias. As used in this case, stratification means that each variable (or stratum) such as location, occupation and time can be ordered or arranged such that, in turn, each element within each stratum, (such as specific location, specific occupation or time interval) can be selected randomly, using the techniques of probability theory. Briefly, each shift is broken down into a number of sampling time intervals, each interval corresponding to a specific time of day. A frequency of sampling, along with a table of random numbers, (corresponding, say, to all locations which are to be sampled) is established according to the baseline variation of concentration measurements for each location. Each sampling interval is then ordered such that sampling is done, as the shift progresses, at locations (on a level or in a particular section of a mine) which have been determined randomly. If a third stratum (say occupation) is required this may be incorporated as a third "dimension" in the random plan. Not only does this scheme provide for the most efficient use of sampling time, but helps assure that bias is not introduced in having a repetitious sampling route or other similar practice. Moreover, the frequency of sampling required for each stratum is determined by the inherent variability of the concentrations measured for each location, say, within the stratum. The concentrations of radon daughters measured in each location are multiplied by the time each worker spends in that location. The sum of all such products for each individual is the "best estimate" of exposure for that individual under this particular sampling plan.

IMPOSITION OF LIMITED PERSONAL DOSIMETRY FOR RADON DAUGHTERS

It is not the purpose here to review the state of the art of personal dosimeter development and use for the monitoring of radon daughters. The subject has been addressed in a number of reviews (NEA, 1979; Stocker, 1979; Stocker, 1980) in the last few years and the most recent innovations and results are being presented in other sessions at this conference.

Rather, the purpose is to explain the transition from conventional (non-randomized) grab sampling and time weighting to a system of limited personal dosimetry for radon daughters. The technological advances are alluded to only insofar as they illustrate the progression in the thinking which led to the imposition.

As has been mentioned, the reporting of radon daughter exposures by the uranium mining companies has been based on the system of conventional grab sampling and time weighting. This method of reporting persists to the present day and even after the imposition of the limited system of personal dosimetry, the AECB will continue to insist on the recording (and reporting) of both systems, for a period of several years. This will afford the opportunity for comparing the two systems and for discovering any limitations in the newly-imposed system. It will also serve to illustrate systematic differences between the two systems and to quantify these differences.

In 1976, the AECB, together with the Department of Energy, Mines and Resources, (EMR) became actively involved in two personal dosimeter evaluation programs through research contracts (Yourt, 1976; Phillips and Pai, 1978). These were followed by a number of additional evaluations (Yourt, 1978; Phillips, Pai and Jokura, 1979), some involving the collaboration of the Commissariat à l'Energie Nucléaire of France, but once again carried out under research contracts in Canada. For the past few years, EMR has performed evaluations, in-house, to augment the work of private sector and university contracts. Independently, one Canadian manufacturer (with aid from EMR and the U.S. Bureau of Mines) has developed a device which may be used as a personal dosimeter.

The litany of trials and tribulations of each dosimeter evaluation program has been given elsewhere (Stocker, 1979; Stocker, 1980; Bigu et al., 1981). Suffice it to say that, through theoretical study and experimental investigations in the laboratory and in several underground mines, many modifications to the basic electro-mechanical systems have resulted in improved accuracy, precision and reliability in most of the dosimeters evaluated. That is not to say, however, that the present systems are entirely problem free. Some unusual and inconsistent results persist in terms of plate-out, mechanical integrity, volume of air sampled, particle detection and read-out, energy discrimination and "interferences" of unwanted radiation. There is also the additional requirement, recently imposed by the AECB, that radon daughters and thoron daughters be monitored independently. However, a sufficient amount of work has been performed to date in Canada and this, integrated with the work which has been carried out in France, in the U.S.A. and to a lesser extent in other countries, has been deemed sufficient justification (for the present) for the AECB to make mandatory some limited use of personal devices for radon daughter exposure estimation. This is not to minimize the deliberation and hesitation which have gone into this decision. It still leaves open the degree to which the limited program will be applied and recognizes that further research effort is needed to minimize or eliminate lingering deficiencies with the existing systems.

An indication of the comparative results of concentrations derived from grab sampling and from the integrated exposure using personal dosimeters over the same period are given in Fig. 3. Since some differences appear to exist between these two measures of the radon daughter concentrations, it remains still to account for these differences. These may be related to plate-out and size-selection differences between the open-face grab-sampling methods and those of the personal devices in which the inducted air must make a circuitous path around one or more corners.

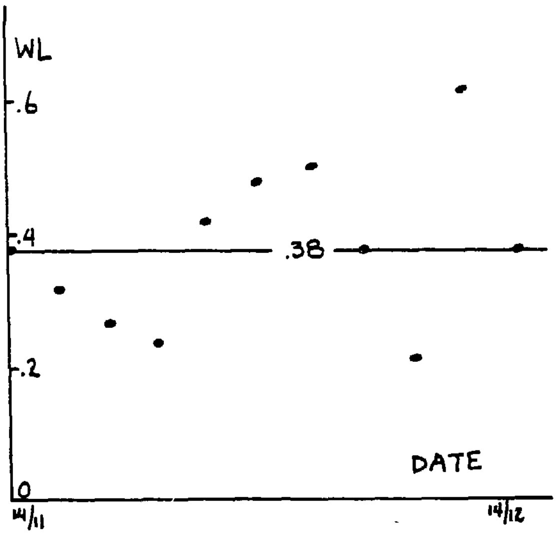

FIGURE 3. Average radon daughter concentration from a personal integrating dosimeter (solid line) compared to grab-sample measurements (•) over the same one-month period. (Adapted from Phillips, Pai and Jokura, 1979).

While it seems intuitively clear that "personal" integrating devices give better estimates of "personal" exposure than do grab-sampling and time-weighting methods, one cannot conclude from the example given in Fig. 3 that "personal" devices give the fundamental measure of concentration. Only the differences between the two methods are demonstrated. Other, more recent, measurements seem to point to systematic differences between the two methods of estimation (Bigu et al., 1981).

These results raise the questions as to which method of estimation is the "fundamental" (i.e., more accurate) one, how the two methods are related and whether the working level is adequately defined. These questions, while requiring attention in the immediate future, are beyond the scope of this presentation.

CONCLUSION

Several aspects of the broader implications of compliance with an individual exposure limit have been presented. These implications depend on the errors associated with the measurements of concentrations and times which are used to estimate the individual's exposure. The random and non-random errors have been separated and some methods for dealing with these have been suggested. Such suggestions have included standardization of grab-sampling techniques, stratification of shift sampling times and adoption of personal integrating devices. While not all the details have been worked out, it seems clear that the evolution of individual exposure estimation of radon daughters for uranium miners is moving toward a system of personal dosimetry, perhaps limited to certain miners or work situations. There appears also to be greater acceptance on the part of the miners to have their individual exposures assigned on the basis of their personally-worn devices.

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