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U.S. Department of Energy
Radiological Control Coordinating Committee
Radon Subcommittee

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Radon Subcommittee, G.E. Runkle, Chair
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OCCUPATIONAL EXPOSURE TO RADON AND THORON

Executive Summary

Because of past and present DOE activities, workers at some DOE sites are occupationally exposed to elevated levels of the radioactive gases radon and thoron, and their airborne, short-lived radioactive decay products. These exposures cannot be measured by bioassay and are generally not currently being assigned to workers' radiation exposure records. At facilities where enhanced radon and thoron may contribute to occupational exposure, 10 CFR 835 requires that an internal dose evaluation program be implemented. DOE's 10 CFR 835 requires personnel and workplace monitoring thresholds for radon that are comparable to natural background levels, resulting in technical difficulty in distinguishing occupational exposure from background exposure. To achieve compliance with 10 CFR 835, at some sites most general employees would have to be designated and trained as radiological workers because of the potential for occupational radon exposures. The Radon Subcommittee of the Radiological Control Coordinating Committee (RCCC) was formed to address these problems.

This document provides an overview of accepted terminology and current national and international recommendations and regulations applicable to radon and thoron exposures. It details traditional occupational exposure limits for radon and thoron progeny. These limits have historically been expressed as potential alpha energy exposure (measured in working level months, WLM) rather than as total effective dose equivalent (measured in rems). The traditional limits have recently been re-evaluated on the basis of risk. This re-evaluation has led the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) to adopt a 1994 dose conversion convention that reduces the number of rems per WLM by a factor of 2.5.

The Radon Subcommittee evaluated regulatory alternatives ranging from maintaining the current regulatory requirements to deregulating radon in the workplace. The two recommended alternatives to the current 10 CFR 835 are: 1) raising four regulatory thresholds for radon and thoron (personnel monitoring, workplace monitoring, controlled area, and being classified as a radiological worker); and 2) adopting derived air concentration values based on the 1994 dose conversion convention of the ICRP and the IAEA.

This document discusses radon and thoron measurements, monitoring, dose evaluation, management of exposures, and an ALARA program. The Radon Subcommittee recommends changes to 10 CFR 835, development of new regulatory guidance, and identifies research and development needs for radon and thoron and their progeny.

OCCUPATIONAL EXPOSURE TO RADON AND THORON

1.0 RADON AND THORON IN THE DOE

Residual radium and thorium produced during DOE activities have the potential to cause occupational exposure to radon, thoron, and their short-lived progeny. Studies of miners in uranium and other underground mines have shown that high exposures to the short-lived progeny of radon significantly increase the risk of lung cancer in human beings, especially among smokers (NAS 1988, ICRP 1994).

Many of the radium- and thorium-bearing materials in the DOE are in the form of wastes or residues from the materials production facilities and mining and milling operations. A 1990 DOE indoor radon study revealed an average indoor radon concentration of 0.91 pCi/L, and identified 86 buildings at 26 different sites with radon levels at or above 3.6 pCi/L (DOE 1990). In a 1992 report for compliance with National Emission Standards for Hazardous Air Pollutants, twelve DOE facilities and projects[1] were identified with elevated radon levels (DOE 1992b). Additional sources of radon and thoron exposure may exist for workers in the Uranium Mill Tailings Remedial Action (UMTRA) Project and the Formerly Utilized Sites Remedial Action Program (FUSRAP), since radium is associated with uranium ore and uranium mill tailings. The Fernald Environmental Management Project (FEMP) is of particular concern.

At the FEMP, remediation activities currently expose workers to elevated levels of radon and thoron. While the levels vary, workplace radon concentrations as high as 100 pCi/L have been measured, concentrations that are clearly elevated, given normal outdoor background levels of less than 1 pCi/L. Average fence line concentrations at the FEMP were 0.63 ± 0.20 pCi/L in 1993, and 0.59 ± 0.29 pCi/L in 1992 (FERMCO 1994).

The contractors responsible for radiological programs at some DOE sites have independently implemented their own programs for monitoring and limiting exposure. These programs include the use of standard health physics practices such as workplace monitoring, engineered controls, administrative controls, and respiratory protection.

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[1] The twelve DOE facilities and projects are Argonne National Laboratory, Bettis Atomic Power Laboratory, Fernald Environmental Management Project, Hanford Site, Haywood Interim Storage Site, Hazelwood Interim Storage Site, Middlesex Sampling Plant, Mound Plant, New Brunswick Site, Niagara Falls Storage Site, Wayne Interim Storage Site, and Weldon Springs Site Remedial Action Project.

2.0 RADON AND THORON TERMINOLOGY

The chemical element radon has two radiologically important isotopes that occur in nature: radon-220 and radon-222. Following popular usage, this document refers to the former as "thoron" and the latter as "radon."

Radon and its short-lived progeny (decay products) are continuously produced by decay of radium-226, a member of the naturally occurring uranium-238 series. Airborne concentrations of radon's short-lived progeny (polonium-218, lead-214, bismuth-214, and polonium-214) are of interest due to their potential for deposition in the lung, leading to subsequent irradiation of lung tissue by alpha emissions from polonium-218 and polonium-214.

Thoron and its short-lived progeny are produced naturally and continuously from decay of thorium-232. In contrast with radon, substantially less thoron reaches the breathing zone because of its short half-life (56 seconds compared with 3.8 days for radon).

In air, there is a complex and dynamic relationship between radon and thoron and their short-lived progeny (decay products). As a result, many physical quantities and units (Table 1) are used in discussing the risk due to radon and thoron in the workplace. Because the progeny may not be in radioactive equilibrium with the parent, or may be removed from air through plate-out and other processes, the “equilibrium factor” is used to describe the fraction of maximum possible progeny present based on the amount of radon present. Radon dosimetry is strongly dependent on the equilibrium factor.

Table 1. Terms Used for Radon and Thoron and Their Progeny[a]

Abbreviation	Term	Description
pCi/L	Picocuries per liter	Activity of radioactive gas (radon or thoron) per unit volume of air
PAEC	Potential alpha energy concentration	Amount of alpha particle energy potentially emitted by any mixture of radon or thoron progeny per unit volume of air
WL	Working level	Unit of PAEC
PAEE	Potential alpha energy exposure	Average PAEC × worker's exposure time
WLM	Working level month	Average PAEC × worker's exposure time; 1 "Month" = 170 hours
F	Equilibrium factor	Fraction of possible PAEC (in WL) present given the amount of radon or thoron present F = (PAEC × 100) / (radon conc.) F = (PAEC × 7.43) / (thoron conc.)
EEC	Equilibrium equivalent concentration	Radon or thoron concentration that would be present if F = 1; EEC = F × (radon or thoron conc.)

[a]Based on ICRP 1981, 1986, 1994; NCRP 1984, 1988; NEA 1983.

Throughout this document, the terms "radon" and "thoron" are used most often to include the short-lived progeny of radon and thoron, respectively, not necessarily in equilibrium. The terms "radon concentration" and "thoron concentration," however, refer to the concentration of the respective parent nuclide alone.

3.0 CURRENT REGULATIONS AND GUIDANCE FOR RADON AND THORON

Current regulations and recommendations for protection against radon and thoron progeny in the workplace are summarized in Table 2.

3.1 Recommendations

International recommendations for protection against radon have been given by the International Commission on Radiological Protection (ICRP) in several publications (1981, 1986, 1991, and 1994). For radiological workers, ICRP (1994) adopts a dose conversion convention of 0.5 rem effective dose[2] per working level month (WLM). ICRP recommendations limit workers to 10 WLM (5 rems/year) in any single year[3]. The ICRP recommends that the dose conversion convention be employed to translate radon exposure into effective dose, which should then be added to the other effective doses (external and internal doses) for overall assessment. The ICRP (1994) uses a default indoor equilibrium factor of 0.4 for radon. The International Atomic Energy Agency (IAEA; 1994) has recently adopted the ICRP recommendations, and also made recommendations for thoron.

In the USA, current national recommendations are given by the National Council on Radiation Protection and Measurements (NCRP). The U.S. Environmental Protection Agency (EPA) sets Federal Standards. The U.S. Nuclear Regulatory Commission (NRC) and DOE base their radiation protection standards on Federal guidance and consideration of recommendations of national and international expert groups such as National Academy of Sciences, NCRP, ICRP, IAEA, as well as scientific literature.

The NCRP recommends effective dose limitations in the workplace of 5 rems in any one year and (Age × 1 rem) as a lifetime limit (NCRP 1993). Although it does not directly address exposure to radon and thoron progeny in the workplace, the NCRP (1993, p. 49) adopts the 1981 ICRP dose conversion convention of 1 rem of effective dose equivalent per WLM from radon; this convention would lead to 5 WLM in any one year and (Age × 1 WLM) as a lifetime limit. The NCRP Report was issued more than a year before the 1994 ICRP Publication 65. Using the 1994 ICRP dose conversion convention, the NCRP limits would increase to 10 WLM (5 rems) in any one year and (Age × 2 WLM or Age × 1 rem) as a lifetime limit.

3.2 Regulations

Current NRC (1991) regulations limit radon and thoron progeny exposures, respectively, to 4 WLM and 12 WLM per year and adopt derived air concentrations (DACs) of 1/3 working level (WL) and 1 WL. The EPA (1988) has adopted limits of 4 WLM for radon and 12 WLM for thoron. The DOE (1989, 1993) sets DACs

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2 Effective dose equivalent and effective dose are essentially the same for radon and thoron. See Appendix, section A.3.1.

3 The 1994 ICRP dose conversion convention of 0.5 rem/WLM is independent of, and unaffected by, the ICRP five-year average dose limit of 2 rems per year. It is purely coincidental that in 1990 ICRP reduced its 5-year average dose limit by a factor of 2.5, and in 1994 increased the dose conversion convention for radon by a factor of 2.5.

of 1/3 WL and 1 WL for radon and thoron progeny exposures, respectively, as found in DOE Order 5480.11 (including the draft revision of May 1993) and 10 CFR 835.

In the UK, Canada, and France, current or proposed regulations essentially implement the 1986 ICRP guidance (ICRP 1986, UK 1988, France 1989, Canada 1991). Australia and South Africa have lower limits. Appendix B provides a summary of the radiation protection regulations used in other countries.

Table 2. Summary of Current National and International Recommendations and Regulations Concerning Limits for Radon and Thoron Exposure in the Workplace

	Potential Alpha Energy Concentration		Potential Alpha Energy Exposure**	
Reference	Radon	Thoron	Radon	Thoron
EPA 1988; NRC 1991; USDOE 1989, 1993	1/3 WL*	1 WL	4 WLM* per year	12 WLM per year
ICRP 1986, Canada 1991, UK 1988, France 1989	0.4 WL	1.2 WL	4.8 WLM per year	14.1 WLM per year
NCRP 1993 (as written, based on 1981 ICRP dose conversion convention)	-	-	5 WLM (= 5 rems) in any one year; age × 1 WLM (= 1 rem) as lifetime limit†	-
NCRP 1993 (if revised using the 1994 ICRP dose conversion convention)	-	-	10 WLM (= 5 rems) in any one year; age × 2 WLM (= 1 rem) as lifetime limit†	-
ICRP 1994, IAEA 1994	-	-	10 WLM (= 5 rems) in any one year; 4 WLM (= 2 rems) per year averaged over 5 years	IAEA only: 30 WLM (= 5 rems) in any one year; 10 WLM (= 2 rems) per year averaged over 5 years

Notes: *WL = Working Level; WLM = Working Level Month; all “rems” are committed effective dose equivalent or committed effective dose.
** NRC terms this "Annual Limit on Intake."
† The NCRP does not directly address workplace radon and thoron exposures; their approach to homes can be applied to the workplace.

4.0 REGULATORY CONTROL OF OCCUPATIONAL EXPOSURE TO RADON AND THORON

According to the ICRP (1991) and NCRP (1993), there are "two circumstances of exposure to radiation, one where human activities introduce new sources or modes of exposure and thus increase the overall exposure" (practices) "and the other where human activities decrease the exposure to existing sources" (intervention). "In the workplace, there is sometimes difficulty in making a sharp distinction between radon [and thoron] concentrations that should be treated as being due to a practice or as due to an existing situation for which intervention may be needed" (ICRP 1994).

For the purposes of this document, "practices" in the DOE include present or former activities that result in radon and thoron concentrations above background ("elevated" radon and thoron levels) due to the presence of residual radium and thorium from DOE's production mission. Elevated radon and thoron concentrations not due to DOE activities may occur in the DOE, as in any workplace. Such concentrations in any workplace may call for intervention. It is important to distinguish between DOE activities, which clearly lead to occupational exposures that should be controlled, and situations that may require intervention. Significantly different standards are appropriate for the two situations (NCRP 1993; ICRP 1991, 1994).

For completeness, the Subcommittee notes that declared pregnant workers require no special consideration for protection from radon and thoron, because the dose to the embryo/fetus is insignificant compared with the dose to the respiratory tract.

4.1 Populations of Interest

The size and scope of an occupational radon and thoron exposure control program is dictated by the definition of occupational exposure. Based on the source of the radon or thoron, two distinct populations of workers can be defined:

1) Those radiological workers exposed to radon and thoron from past and present DOE activities involving residual radium- and thorium-bearing material;

2) Those workers exposed to enhanced concentrations of radon and thoron due to causes other than DOE activities, that is, individuals whose radon and thoron exposures are due to naturally occurring radon and thoron sources that may or may not have been technologically enhanced, for example, by buildings that permit entry of radon soil gas or by building materials containing significant amounts of radium or thorium. Some individuals in this group may have exposures that are high enough to warrant intervention.

Those workers in Population 1 are representative of the workers at the FEMP and UMTRA sites. Because the source is due to DOE activities, this population should be considered to be occupationally exposed. The combined total number of workers at both the FEMP and UMTRA sites with the potential for exposure is approximately 3,000. The radon concentrations at these sites are variable. Concentrations due to DOE activities at the FEMP have been observed to be as high as 100 pCi/L.

Population 2 includes DOE workers, subcontractors and visitors, and also Population 1. Any DOE site where elevated radon and thoron levels exist could be considered for intervention. While the workers in Population 2 number in the tens of thousands, the number of affected workers in Population 1 is probably small. In 1993, Oak Ridge National Laboratory (ORNL) developed a model that could estimate indoor radon distributions at a given site using limited site screening data. The model was based on 10,000 radon measurements collected in various Federal buildings from 1989 to 1993. Using radon screening data collected by UNC Geotech from 20 DOE sites, ORNL estimated that 1.3% of the work areas at those sites contained radon progeny levels in excess of 0.02 WL.

In Population 2, it is difficult to estimate the number of workers for whom intervention may be needed. Elevated levels of radon have been measured at some DOE facilities such as in storage vaults at Rocky Flats and in manholes at the FEMP. Although this source of exposure is not due to DOE-processed residues, the increased concentrations can be attributed to the creation of a confined atmosphere.

The Radon Subcommittee chose to limit scope of this document to the issues concerning of Population 1.

4.2 New International Recommendations for Radon and Thoron

As shown in Table 2, traditional limits for exposure to radon and thoron progeny are expressed in WLM rather than in total effective dose equivalent (TEDE), which is the current DOE practice for limiting all other occupational radiation exposures.

The estimated risk of lung cancer per WLM of exposure has essentially not changed over the 14 years since ICRP Publication 32 appeared (ICRP 1981, 1986, 1994; NAS 1988, Lubin et al. 1994). However, with the reassessment of the atomic bomb survivor doses and the occurrence of increasing numbers of excess cancers in the Japanese bomb survivors, the expectation of harm ("detriment," i.e., fatal and nonfatal cancer and hereditary ill-health) per rem has increased from 1.25×10^{-4} (ICRP 1977) to 4×10^{-4} (ICRP 1991; NAS 1990; UNSCEAR 1988, 1993). Neither old (ICRP 1981, NEA 1983) nor new (Birchall and James 1994, ICRP 1994, James 1994) respiratory tract dosimetry calculations support a reduction in the conversion between potential alpha energy exposure (PAEE) and calculated effective dose (i.e., rems/WLM). However, in order to avoid overestimating radon risk, the ICRP has adopted a dose conversion convention of 0.5 rem effective dose per WLM (ICRP 1994). According to the ICRP (1994), 10 WLM carries the same risk as 5 rems of TEDE. This ICRP recommendation has been adopted by the IAEA (1994).

Historically, the PAEE limit for thoron has been 3 times that for radon (ICRP 1981, 1986; EPA 1988). While the ICRP (1994) has recently revised its recommendations on radon, they did not address thoron. There is no human epidemiological evidence for determining risk from thoron progeny, so traditional dosimetric extrapolation from radon is used. The Organization for Economic Cooperation and Development's Nuclear Energy Agency expert group concluded that "the effective dose equivalent per unit of exposure to radon-220-daughter potential α-energy is thus approximately 1/3 that for the radon-222-daughters" (NEA 1983). James (1994) used the new ICRP Lung Model to conclude that the "exposure-dose coefficients for thoron-progeny are approximately one-third of the corresponding values for radon progeny." The recent IAEA interim basic safety standards raise the annual (i.e., 5-rem) limit on exposure for thoron decay products from 12 WLM to 30 WLM (IAEA 1994; Table II-I). Adopting the IAEA standards would have the effect of raising the DOE's thoron progeny DAC from 1 WL to 2.5 WL. Thus, thoron produces one-third of the effective dose for the same potential alpha energy concentration (PAEC) as does radon.

The Radon Subcommittee recommends that

- *The DOE should consider changing the derived air concentration (DAC) values published in 10 CFR 835 for radon and thoron to reflect current recommendations from ICRP and IAEA. Specifically, the DOE should consider changing the DAC for radon in footnote 4 for Appendix A of 10 CFR 835 from 1/3 WL to 5/6 WL, and changing the DAC for thoron from 1 WL to 2.5 WL. These correspond to annual PAEE limits of 10 WLM and 30 WLM, respectively, for radon and thoron. If this change is made, the corresponding equilibrium equivalent DACs in Appendix A of 10 CFR 835 for radon and thoron must then be changed to 83 pCi/L and 19 pCi/L (8.3 E-08 and 1.9 E-08 μCi/mL), respectively. Based on ICRP recommendations, the new equilibrium equivalent DAC values represent an increase by a factor of 2.5, and would put DOE's radiation protection standards for radon and thoron on the same risk basis as other radionuclides.*

4.3 Regulatory Control of Radon Exposures

Assessment of committed effective dose equivalent from exposures to radon and thoron must be done to calculate a worker's TEDE. Due to the short half-lives and rapid lung clearance of their progeny, there is no practical bioassay technique for assessing radon and thoron exposures. Therefore, the usual practice of worker monitoring using bioassay is not feasible. The only practical recourse is to measure radon, radon progeny, or thoron progeny[4] in the workplace air, and to track worker exposure time. These results can be used to determine the PAEE in WLM or the equilibrium-equivalent radon exposure in DAC-hours. The committed effective dose equivalent from radon can then be determined by multiplying the PAEE in WLM by a dose conversion coefficient in rems per WLM, or by multiplying the equilibrium-equivalent radon exposure in DAC-hours by 5 rems per 2000 DAC-hours. This committed effective dose equivalent can then be added to effective dose equivalent (external exposure) and committed effective dose equivalent (exposure from intakes of radionuclides) to yield total effective dose equivalent (TEDE). Technical discussions supporting the need for a dose conversion factor are given in Appendix sections A.3.4 and A.3.5

Dose determined from air concentration measurements is strongly affected by any respiratory protection worn by workers. Because individual respiratory fit factors measured under test conditions are usually greater than the protection afforded by respirators in actual workplace situations, guidance on the use of assigned protection factors for dose calculations is needed.

To ensure consistent and proper use of PAEE and EEC measurement quantities across the DOE, the Radon Subcommittee recommends

- *The DOE should consolidate definitions of radiological terms for radon and thoron in 10 CFR 835.2. New and modified definitions are given in Section 7.2.*

- *The DOE should provide regulatory guidance for conversion of worker stay times and PAEC or radon and thoron concentration measurements to PAEE in working level months (WLM) or equilibrium equivalent DAC-hours.*

- *The DOE should adopt explicit dose conversion factors for radon and thoron to convert PAEE in working level months to rems of committed effective dose equivalent. The dose conversion factors implicit in 10 CFR 835 are currently 1.25 rems/WLM for radon, and three times less, i.e., 0.42 rem/WLM, for thoron. Note: if DOE chooses to adopt the ICRP/IAEA dose conversion factors (refer to section 7.1, Regulatory Alternative 2, below), the conversion factors are 0.5 rem/WLM for radon, and 1/6 rem/WLM for thoron.*

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[4] There is no practical way to make a continuous thoron measurement at environmental levels.

- *The DOE should provide explicit guidance for calculating committed dose equivalent to lung, and intakes and identities of radon, thoron and their progeny as required by 10 CFR 835.702(c)(4).*

- *The DOE should develop guidance for use of assigned protection factors for respirators in radon and thoron dose calculations.*

- *The PAEC, PAEE, and the effective dose equivalent from radon should be documented and retained by each affected facility. Modifications to existing DOE Implementation Guides (e.g., internal dosimetry, workplace air monitoring) and new guidance concerning recordkeeping should be developed.*

A technical discussion of the difficulties caused by round-off errors when converting from equilibrium equivalent concentration to PAEC and vice versa is given in Appendix A.3.6.

5.0 RADON AND THORON MEASUREMENTS, MONITORING, AND DOSE EVALUATION

Prior to establishing an occupational radon and thoron monitoring program, a radiation protection program must establish the quantities of interest and the levels that trigger monitoring. An occupational radon and thoron measurement program involves characterizing work sites to identify areas of concern and to establish where routine monitoring may be required. Routine monitoring may include both individual worker and general area monitoring, depending on the ambient PAEC.

5.1 Quantities of Interest and Measurement Methods

The worker's cumulative occupational exposure or potential alpha energy exposure (PAEE) in WLM can be calculated from the time-weighted average PAEC, measured in WL, multiplied by the time spent (in "working months" of 170 hours each) in that environment. Alternatively, measurements of radon (but not thoron) concentration can be made, along with measurements or assumptions about equilibrium factors, to deduce PAEE in WLM or equilibrium-equivalent radon exposure in DAC-hours.

For radon exposure in the absence of significant concentrations of thoron, the least expensive and most practical approach is to measure radon concentration and use the equilibrium factor to estimate the equilibrium equivalent concentration (EEC) of radon and thus the PAEC. The advantages of this measurement protocol are the simplicity and cost effectiveness of measuring radon rather than radon progeny. A large variety of passive detectors can be used as both personal and area radon monitors. A disadvantage is the inaccuracy associated with variable equilibrium factors. However, variation in the equilibrium factor is partially offset by a compensating variation in the unattached fraction[5] of potential alpha energy. The amount of dose per unit radon concentration decreases with decreasing equilibrium factor if the unattached fraction is constant. However, the unattached fraction is not constant, but increases with decreasing equilibrium factor, causing the dose per unit radon concentration to increase. Because of these competing effects, the dose per unit radon concentration is not as strongly linked to equilibrium factor as formerly believed (James et al. 1988).

Since the equilibrium factor may vary from one environment to another, representative values should be obtained by actual measurements and by a review of the literature for data under similar conditions. For indoor measurements, there are sufficient data on equilibrium factors with an average around 0.4, the default value adopted by the ICRP (1994). Data collected in various indoor environments show that the equilibrium factors for radon progeny vary within relatively narrow limits (NCRP 1984, 1988; NAS 1991). However, for outdoor situations, the equilibrium factor and unattached fraction are more variable and depend on many factors, including radon and thoron diffusion, age of the air, and meteorological conditions at the time of exposure. If equilibrium values are not available or are impractical to collect, default values reflecting past experience under similar operating conditions may be used.

A currently practical approach is to measure PAEC using continuous or integrating instruments worn by the workers or used as area monitors. These instruments measure the total PAEC irrespective of the characteristics of the inhaled radon and thoron progeny.

An ideal measurement for assessing occupational exposure to radon and thoron progeny would be to determine the potential alpha energy deposited in the tracheobronchial region of the respiratory tract. This quantity would take into account the particle size distribution of the radon progeny. Since the majority of lung cancers among uranium miners occurred in the bronchi, it would be best to use instruments that mimic the collection characteristics of the tracheobronchial region. Prototype instruments are available, but currently their bulk, fragility and expense make them impractical for field use (George and Knutson 1992; Wright et al. 1992). The response of a practical instrument of this nature would need to be calibrated in terms of an accepted dose conversion convention.

The Radon Subcommittee recommends that

[5] Radon and thoron progeny may attach themselves to airborne dust or other aerosols. The fraction of progeny that are not so attached is called the “unattached fraction.”

- *The DOE should provide regulatory guidance for measurements of workplace radon and thoron concentrations, potential alpha energy concentrations, and measurements of (or assumptions about) equilibrium factors.*

5.2 Workplace Characterization

Workplaces should be evaluated for their potential for producing annual exposures in excess of regulatory action levels. Screening measurements, either newly performed or from existing databases, should be evaluated to identify areas requiring further evaluation and control. In general, normal above-ground offices and outdoor work areas with no history of radium or thorium contamination should not require further evaluation. Mines, underground tunnels, outdoor areas with significant concentrations of radium-226 in soil and indoor areas with any history of radium or thorium contamination should be evaluated through further measurements. Each area may need evaluation on a case-by-case basis. For example, areas with high radium-226 concentrations but low annual occupancy may not require further evaluation.

5.3 Background Levels of Radon and Thoron

Because radon and thoron are widespread in the environment and the required monitoring thresholds are relatively low, field implementation of the current limits in 10 CFR 835 is impractical with today's technology. For example, in some cases worker and visitor monitoring programs would be required at radon and thoron levels that are indistinguishable from natural background. The difficulty in monitoring visitors and workers using the DACs currently implemented in 10 CFR 835 is illustrated in Figure 1, a graph showing monitoring thresholds (not including background) and radon monitoring results from the Fernald Environmental Restoration Project.

Radon Concentrations at the FEMP

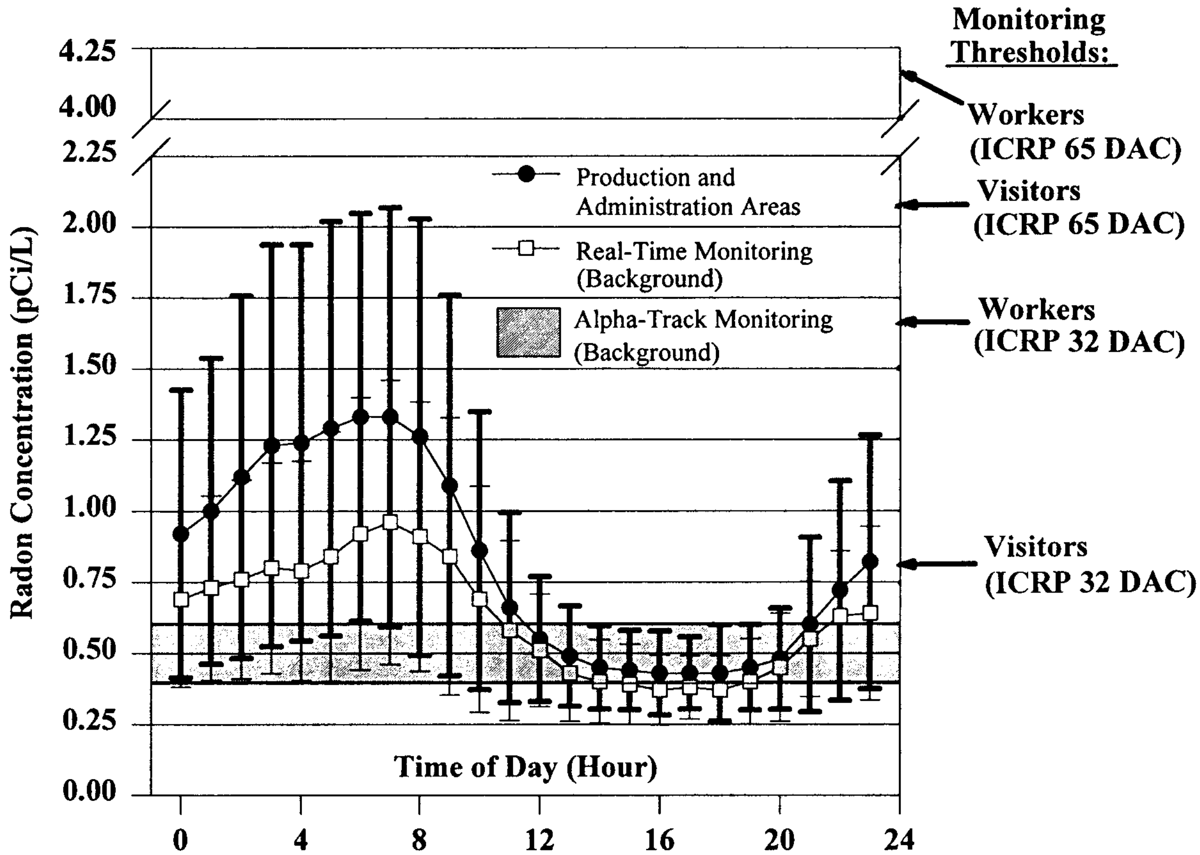

Figure 1. Radon Concentrations at the FEMP. The figure shows three different sets of radon monitoring results at the FEMP and various monitoring thresholds for continuous occupancy. The shaded region represents long-term alpha-track monitoring results (year-long). The data points with error bars show the variations recorded by real-time monitoring instruments at various times of the day in production and administration areas (black dots with thick error bars) and background measurements (open squares with thin error bars). The error bars represent the range containing 68% of the results. The monitoring thresholds based on the DOE's current 10 CFR 835 DACs, based on ICRP Publication 32, fall within the normal fluctuations of background, while monitoring thresholds based on the DACs derived from the 1994 recommendations of ICRP and IAEA fall above most of the normal fluctuations in background. A description of the calculation of the monitoring thresholds is given in Section A.3.2 of the appendix.

When evaluating the potential exposure of workers to radon or thoron progeny resulting from DOE activities, only exposures above background are of interest. The preferred background to use is the measured radon or thoron concentrations or PAECs that would exist without the DOE activities. For outdoor measurements, an appropriate background value sometimes may be obtainable only by off-site measurements. For buildings, further guidance is needed. Therefore, the Radon Subcommittee recommends that

- *The DOE should develop guidance on the determination of radon and thoron background.*

High radon and thoron background values in the workplace may indicate a need for intervention. The Radon Subcommittee recommends that

- *The DOE should not permit correcting for relatively high background PAECs without investigation of the source of the high background value.*

5.4 Exposure Monitoring

Exposure monitoring is required by 10 CFR 835 when workers have the potential to be exposed in excess of regulatory action levels for radon or thoron progeny. Once the decision has been made to initiate a radon and thoron measurement program, two objectives must be met by the program. The first objective is to characterize in real time the potential exposure that workers might receive by being present in an area of concern. The second objective is to establish the exposure of record that each worker actually receives.

While workers are present, a minimum monitoring program should consist of either frequent grab samples or using a continuous area monitor that produces real-time data output. Using a continuous monitor will generally be more economical than collecting grab samples, due to the labor-intensive nature of the latter activity. For purposes of documenting radon progeny exposure, monitoring of the radon progeny is always preferred over monitoring radon concentration. However, if the equilibrium between radon and its progeny has been appropriately characterized, continuous radon concentration monitoring with application of a suitable equilibrium factor may be acceptable. At many work sites (e.g., outdoors) the equilibrium may be highly variable, and personal radon progeny monitoring may be required. For documenting thoron progeny exposure, only progeny monitoring is acceptable; this is due to the poor correlation between thoron concentration and thoron progeny concentration (i.e., the thoron progeny equilibrium factor is highly variable).

5.5 Selection of Instrumentation

The instruments chosen for general area monitoring should be of the continuous, real-time type. There are many such instruments commercially available. It is recommended that DOE conduct a review of instrumentation technologies to evaluate the current suitability for specific applications. The instrument chosen should satisfy the applicable guidelines of ANSI N42.17A (ANSI 1989). The most critical characteristics to assess are the resistances to the various environmental influences in the workplace, where the effects of temperature, humidity, light, vibration, radio frequency interference, and electromagnetic pulses may be of concern.

Most instruments are not designed for unprotected outdoor operation. Therefore, if the work is located outdoors, some degree of protection from adverse environmental conditions is required. Particular care in designing this protection is necessary so that the validity of the measurement is not compromised. For instruments measuring radon and thoron progeny, it is particularly important that any such protective enclosure not alter the progeny concentration.

The Radon Subcommittee recommends

- *The DOE should evaluate available personal air samplers for monitoring radon and thoron progeny exposure to workers.*
- *The DOE should establish performance criteria for instruments used to characterize airborne radon and thoron and their progeny in the DOE.*
- *The DOE should support development of improved radon- and thoron-measuring instrumentation.*

5.6 Calibration of Instruments and Quality Control

All instruments need annual or more frequent calibration, depending on their performance characteristics. The calibration should be performed in a controlled atmosphere that is monitored with instruments whose flow rate and detection efficiency calibrations are traceable to the National Institute of Standards and Technology. Participation in calibration intercomparisons is recommended.

The Radon Subcommittee recommends

- *The DOE should encourage participation by DOE sites in an intercomparison program for radon instrument calibration, precision, and accuracy.*
- *Periodic functional tests should be performed for radon- and thoron-*

measuring instrumentation at a frequency that depends on the performance history of the instrument. As a minimum, these tests should include checks of the air flow rate and reproducibility of detector response. Duplicate measurements should also be performed on a rotating schedule that covers all instruments at least once every two months.

5.7 Additional Training

Training requirements for radiological control technicians in 10 CFR 835, the RadCon Manual, and the DOE Implementation Guide on training do not address the special quantities and units needed for measurements of radon and thoron and their short-lived progeny. As a minimum, technicians should receive training on the origin, nature, and radiological properties and time behavior of radon and thoron and their short-lived progeny, site-specific background, definitions of radon and thoron quantities and units (Table 1), and the measurement of these quantities.

The Radon Subcommittee recommends:

- *The DOE should develop radon and thoron training materials for radiological control technicians.*

6.0 MANAGEMENT OF EXPOSURES AND ALARA PROGRAM

Keeping radiation exposures and releases of radioactive materials to the environment as low as reasonably achievable (ALARA) is a fundamental requirement of every radiological control program. Therefore, exposures to radon and thoron progeny should be kept ALARA. To this end, including radon and thoron progeny exposures in the DOE's TEDE-based system has built-in additivity, which ensures that combined occupational exposures to radiation are below the regulatory limit. This inherent additivity has the effect of reducing the allowable exposure to radon and thoron progeny by an amount dependent upon concurrent exposure to external radiation and other airborne radioactive materials.

When technically and economically feasible, engineering controls should be used instead of administrative controls or respiratory protection devices to control radiological exposure.

The fundamental engineering control methods for control of radon and thoron fall into four categories:

- Remove the source, which may only be practical in cases where the source has been introduced into the workplace by previous DOE activities

- Increase the resistance of the surface material to soil gas entry, a method generally called sealing

- Increase the rate of removal of radon and/or thoron from the work area by increasing the ventilation rate

- Reduce the soil gas influx by reducing or reversing the pressure differential between the building and the soil.

NIOSH (1987), Nazaroff and Nero (1988), and numerous publications from EPA and NCRP discuss the types of engineering control methods for radon and thoron, including their advantages and disadvantages. It is beyond the scope of this report to give details of engineering control methods.

The Radon Subcommittee recommends that

- *Because engineering control methods for radon and thoron can be expensive to implement, their use should be based on cost-benefit analyses.*

Administrative controls may be needed while engineering controls are being implemented or if engineering controls are not feasible. Administrative control methods include scheduling and planning work such that exposures to radon and thoron progeny are minimized. For example, if radon and thoron levels are highest for a particular work area when the barometric pressure is falling or an inversion condition exists, the work could be postponed until the radon and thoron levels have decreased.

The use of respirators should be one of the last options for worker protection. Engineering and administrative controls are more effective means for limiting exposures and providing a safe environment for all workers. Respirator use in a particular workplace is not always practical for a number of reasons, including the additional physiological burden and safety hazards that respirators pose to workers. The safety hazard to large equipment operators is significantly increased by the use of respirators that restrict the operators vision and encumber his movement in the vehicle cab.

7.0 OBSERVATIONS, REGULATORY ALTERNATIVES, AND RECOMMENDATIONS

The Radon Subcommittee presents its observations concerning occupational exposure to radon and thoron in the DOE; two regulatory alternatives to address the current situation; and recommendations for changes to 10 CFR 835, regulatory guidance, and research and development.

7.1 Observations

The Radon Subcommittee makes the following observations:

- Occupational exposures to elevated levels of radon, thoron, and their short-lived progeny occur at some DOE sites.

- Generally, doses are not currently being evaluated and assigned for occupational exposure to radon and its progeny.

- Since there is no practical bioassay method for radon, thoron, and their progeny, dose evaluation must be based on air monitoring data and stay time.

- Personnel and workplace monitoring for radon and radon progeny exposure is impractical at 2% of current ALI as required by 10 CFR 835, because of the potentially large number of people involved and the difficulty of distinguishing such exposures from background.

- The DOE's derived air concentration (DAC) values for radon and thoron in 10 CFR 835 are lower by a factor of 2.5 than the DACs derived from 1994 recommendations of the ICRP and the IAEA.

- In December, 1993, in the preamble to 10 CFR 835, DOE stated that "information for assessing dose from radon exposure will be provided in regulatory guidance currently under development."

These observations are all drivers for change from DOE's regulatory status quo for radon. Below are presented three regulatory alternatives along with their impacts and consequences for DOE. Following these is a summary of the recommendations of the Radon Subcommittee.

7.2 Regulatory Alternatives

The Radon Subcommittee has reviewed the status quo and regulatory alternatives for control of radon and thoron in the DOE, as detailed in Appendix A. The Radon Subcommittee has selected the two most promising alternatives to the status quo (using the current 10 CFR 835 limits for control of radon exposure). These are

- Alternative 1: increasing thresholds for personnel and workplace monitoring from 2% to 10% of current limits for radon and thoron; and

- Alternative 2: increasing the DAC for radon and thoron by a factor of 2.5 to agree with the 1994 recommendations of the ICRP and the IAEA.

The regulatory status quo is not practical because of difficulties in distinguishing occupational exposures from background at monitoring levels required by 10 CFR 835. Regulatory Alternative 1 eliminates both of the objections to the status quo, but creates internal inconsistencies within the regulatory framework that are difficult to justify. These inconsistencies are an apparent double standard for radon and thoron, the existence of radiological workers who are not monitored, and a radon/thoron monitoring threshold that is equal to the administrative control level (500 mrem) for some DOE sites. Regulatory Alternative 2 also eliminates both of the objections to the status quo, has the advantage of being founded on recommendations of the ICRP and IAEA that supersede those on which the current DAC is based, and does not create any of the problems created by Alternative 1. However, there is no consensus in the USA or in the DOE on adopting the ICRP/IAEA recommendations.

7.3 Recommendations

Based on the above analysis, the Radon Subcommittee offers specific recommendations for the evaluation and control of exposure to radon and thoron in three categories: changes to 10 CFR 835, regulatory guidance, and research and development.

7.3.1 Changes to 10 CFR 835

Changes to 10 CFR 835 include the need to choose among regulatory alternatives, add and modify definitions, and explicitly state dose conversion factors.

1. The DOE should consider the following two alternatives to the regulatory status quo:

   Regulatory Alternative 1: Use 10 CFR 835 with increased personnel and workplace monitoring thresholds. DOE would increase the threshold for personnel monitoring in 10 CFR 835.402(c) from 100 mrem CEDE to 500 mrem CEDE in one year. The threshold for workplace monitoring would be increased by changing "2% of an ALI" to "10% of an ALI" in 10 CFR 835.403(a)(1). Thresholds for designating Radiological Worker status and Controlled Areas would also be raised. This would amount to increasing the respective threshold values by a factor of 5.

   Regulatory Alternative 2: Use 10 CFR 835 with revised DAC values based on 1994 recommendations of the ICRP and IAEA. Under this alternative, DOE would change the DAC values published in 10 CFR 835 for radon and thoron to reflect current recommendations from the ICRP and the IAEA. In footnote 4 for Appendix A of 10 CFR 835, the DAC for radon would be changed from 1/3 WL to 5/6 WL, and the DAC for thoron would be changed from 1 WL to 2.5 WL. These correspond to annual potential alpha energy exposure (PAEE) limits of 10 WLM and 30 WLM, respectively, for radon and thoron. The corresponding equilibrium equivalent DACs in Appendix A of 10 CFR 835 for radon and thoron would be changed to 83 pCi/L and 19 pCi/L (8.3 E-08 and 1.9 E-08 μCi/mL), respectively. The proposed DAC values represent an increase by a factor of 2.5.

2. The DOE should adopt explicit dose conversion factors for radon and thoron to convert PAEE in working level months to rems of committed effective dose equivalent. The dose conversion factors implicit in 10 CFR 835 are currently 1.25 rems/WLM for radon and 5/12 rem/WLM for thoron. The DOE should also provide explicit guidance for calculating committed dose equivalent to lung, and intakes and identities of radon, thoron and their progeny as required by 10 CFR 835.702(c)(4). Note: If the DOE chooses to adopt Regulatory Alternative 2 (the ICRP/IAEA dose conversion factors), the conversion factors are 0.5 rem/WLM for radon and 1/6 rem/WLM for thoron.

3. Regardless of the regulatory alternative selected, DOE should modify three definitions in 10 CFR 835.2(b) and add four definitions. The definitions to be modified are committed dose equivalent, committed effective dose equivalent, and dose equivalent. Definitions of potential alpha energy concentration, potential alpha energy exposure, working level, and working level month need to be added to 10 CFR 835.2(b). The existing definition of working level should be removed from the footnote to Appendix A. These modifications and additions are:

- *Committed dose equivalent* ($H_{T,50}$) means the dose equivalent calculated to be received by a tissue or organ over a 50-year period after the intake of a radionuclide into the body. It does not include contributions from radiation sources external to the body. Committed dose equivalent is expressed in units of rem (or sievert). Note: for exposures to the short-lived radioactive progeny of radon-222 and radon-220, see the definition of committed effective dose equivalent.

- *Committed effective dose equivalent* ($H_{E,50}$) means the sum of the committed dose equivalents to various tissues in the body ($H_{T,50}$), each multiplied by the appropriate weighting factor (w_T), that is $H_{E,50} = \Sigma w_T H_{T,50}$. The committed effective dose equivalent is expressed in units of rem (or sievert).

  Note: For exposures to the short-lived radioactive progeny of radon-222, committed effective dose equivalent is calculated directly from workplace measurements of potential alpha energy exposure using a dose conversion factor of 1.25 rem (0.0125 Sv) per Working Level Month. For exposures to the short-lived radioactive progeny of radon-220, committed effective dose equivalent is calculated directly from workplace measurements of potential alpha energy exposure using a dose conversion factor of 5/12 rem (5/1200 Sv) per Working Level Month. Since the lung is the only tissue significantly irradiated by radon and thoron, the committed dose equivalent to lung due to exposures to radon and thoron is calculated by dividing committed effective dose equivalent from radon and thoron by the tissue weighting factor for lung (w_T = 0.12).

[*The following text is used for the note if Regulatory Alternative 2 is selected:*

Note: For exposures to the short-lived radioactive progeny of radon-222, committed effective dose equivalent is calculated directly from workplace measurements of potential alpha energy exposure using a dose conversion factor of 0.5 rem (0.005 Sv) per Working Level Month. For exposures to the short-lived radioactive progeny of radon-220, committed effective dose equivalent is calculated directly from workplace measurements of potential alpha energy exposure using a dose conversion factor 1/6 rem (1/600 Sv) per Working Level Month. Since the lung is the only tissue significantly irradiated by radon and thoron, committed dose equivalent to lung due to exposures to radon and thoron is calculated by dividing committed effective dose equivalent from radon and thoron by the tissue weighting factor for lung, w_{lung} = 0.12:
H_{lung} (from radon and thoron) = $H_{E,50}$ (from radon and thoron) ÷ 0.12.]

- *Dose equivalent (H)* means the product of absorbed dose (D) in rad (or gray) in tissue, a quality factor (Q), and other modifying factors (N). For exposures to the short-lived radioactive progeny of radon-222 and radon-220, see the definition of committed effective dose equivalent. Dose equivalent is expressed in units of rem (or sievert)(1 rem = 0.01 sievert).

- *Potential alpha energy concentration* (PAEC) is the kinetic energy potentially released in a unit volume of air by alpha particles emitted by the short-lived radioactive progeny of radon-222 (i.e., polonium-218 and polonium-214) or radon-220 (i.e., polonium-216, bismuth-212, and polonium-212). PAEC is expressed in Working Levels.

- *Potential alpha energy exposure* (PAEE) is the average potential alpha energy concentration (PAEC) to which a worker is exposed multiplied by the time of exposure in working months of 170 hours -- that is, PAEE = PAEC × time. PAEE is expressed in Working Level Months.

- *Working Level (WL)* is the unit of potential alpha energy concentration, defined as any combination of the short-lived radioactive progeny, in one liter of air without regard to the degree of equilibrium, that will result in the ultimate emission of 1.3E+05 MeV of alpha energy (1 WL = 2.083 E-05 J/m^3).

- *Working Level Month (WLM)* is the unit of potential alpha energy exposure, defined as exposure for 1 working month (of 170 hours) to an airborne concentration of 1 WL. (1 WLM = 1 WL × 170 hours = 0.00354 J·h/m^3).

7.3.2 Regulatory Guidance

The DOE should provide "information for assessing dose from radon exposure ... in regulatory guidance" as stated in the preamble to 10 CFR 835 (58 FR 65484 December 14, 1993). Areas of regulatory guidance should include use of worker stay times, CDE calculations to lung, intakes and identities of nuclides, use of assigned protection factors in dose calculations, what to record and report (e.g., PAEE, PAEC, stay times), what measurements to make, choice of default equilibrium factors, measurement of equilibrium factors, determination of background, background correction, establishment of performance criteria for instruments, participation in intercomparisons, functional tests, QA/QC, RCT training materials, and cost-benefit for engineering controls.

1. The DOE should provide regulatory guidance for conversion of worker stay times and PAEC or radon and thoron concentration measurements to PAEE in working level months (WLM) or equilibrium equivalent DAC-hours.

2. The DOE should also provide explicit guidance for calculating committed dose equivalent to lung, and intakes and identities of radon, thoron and their progeny as required by 10 CFR 835.702(c)(4).

3. The DOE should develop guidance for use of assigned protection factors for respirators in radon and thoron dose calculations.

4. Guidance should be developed for the documenting, recording, and retaining of PAEC, PAEE, and the effective dose equivalent from radon. Modifications to existing DOE Implementation Guides (e.g., internal dosimetry, workplace air monitoring) and new guidance concerning recordkeeping should be developed.

5. The DOE should provide regulatory guidance for measurements of workplace radon and thoron concentrations, potential alpha energy concentrations, and measurements of (or assumptions about) equilibrium factors.

6. The DOE should develop guidance on the determination of radon and thoron background.

7. In its guidance, the DOE should not permit correcting for relatively high background PAECs without investigation of the source of the high background value.

8. The DOE should establish performance criteria for instruments used to characterize airborne radon and thoron and their progeny in the DOE.

9. The DOE should encourage participation by DOE sites in an intercomparison program for radon instrument calibration, precision, and accuracy.

10. The DOE should develop guidance stating that periodic functional tests should be performed at a frequency that depends on the performance history of the instrument. As a minimum, these tests should include checks of the air flow rate and reproducibility of detector response. Duplicate measurements should also be performed on a rotating schedule that covers all instruments at least once every two months.

11. The DOE should develop radon and thoron training materials for general employees, radiological workers, and radiological control technicians.

12. The DOE should develop guidance stating that because engineering control methods for radon and thoron can be expensive to implement, their use should be based on cost-benefit analyses.

13. Since there is no practical bioassay for radon and thoron, exposure monitoring is required when workers have the potential to be exposed in excess of regulatory action levels for radon or thoron progeny. It is important to emphasize the radon and thoron exposure monitoring thresholds as exposure-based (WLM or DAC-hours) versus concentration-based thresholds because of the dynamic nature of radon concentrations.

7.3.3 Research and Development

Research and development needs for radon and thoron include evaluation of personal air samplers, and development of improved instruments.

1. The DOE should evaluate available personal air samplers for monitoring radon and thoron progeny exposure to workers.

2. The DOE should support development of improved radon- and thoron-measuring instrumentation.

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APPENDIX A Discussion of the Status Quo and Regulatory Alternatives for Control of Occupational Radon Exposure

A.1 INTRODUCTION

Currently, 10 CFR Part 835 contains derived air concentration (DAC) limits for the control of occupational exposure to radon and thoron progeny. The limits of 33 pCi/L for radon and 7.5 pCi/L for thoron are based on the recommendations in EPA Federal Guidance Report 11, which in turn are based on ICRP Publication 32.

Since 10 CFR 835 was developed, the ICRP has published new guidance on protection against radon-222 exposure (ICRP 1994). In ICRP Publication 65, an epidemiological evaluation of past radon exposure data resulted in a new dose conversion convention for radon exposure. Assuming an annual dose limit of 5 rems, the 1994 conversion convention of 0.5 rem per WLM would result in an increase in the radon-222 progeny annual exposure limit from 4 WLM (ICRP Publication 32) to 10 WLM (ICRP Publication 65). According to the ICRP (1994), 10 WLM carries the same risk as 5 rems of TEDE. The IAEA has adopted the ICRP's recommendation and also increased the limit for thoron progeny exposure by the same factor, from 12 WLM per year to 30 WLM per year.

This appendix provides an evaluation of the various alternatives available for the regulatory control of radon and thoron exposure. The available alternatives range from maintaining the current regulatory requirements to deregulating radon exposure in the workplace. The appendix also gives a technical discussion of selected topics.

A.2 REGULATORY ALTERNATIVES

A.2.1 Status Quo: Use the current 10 CFR 835 limits for control of radon exposure

A. Technical discussion of status quo

- 10 CFR 835 establishes primary exposure limits and secondary exposure limits that were adopted from Federal Guidance Report 11 (EPA 1988), which is based on ICRP Publications 26, 30, and 32. The primary limits are established as individual dose limits. The secondary exposure limits are established as DAC values for specific radionuclides. Internal and external doses are controlled by limiting the TEDE to less than 5 rems, where internal doses are calculated as committed effective dose equivalents (CEDEs).

- Because a DAC value is presented for radon and thoron in Appendix A of the Rule, a literal interpretation requires that annual exposures to radon and thoron be converted and evaluated as CEDEs and added to the TEDE for comparison with the dose-based limits. Footnotes for Appendix A of 10 CFR 835 state that the DAC values for radon and thoron are based on information given in ICRP Publication 32.

B. Major Advantages

- With adoption of the current DOE radiation protection standards and accepting a DAC value based on ICRP Publication 32, no revision of 10 CFR 835 or the RadCon Manual would be needed.

- No new education and training is needed for general employees and radiological workers, since the current dose reporting system is already covered in radiation protection training programs as specified in the RadCon Manual.

C. Major Disadvantages

- Because of the fluctuation in background radon levels and the lack of DOE guidance on characterizing background radon levels in the workplace, the requirements for monitoring and evaluating exposures to radon are extremely difficult to implement. Additionally, these requirements are not technically feasible at some DOE operations where ambient background radon levels exceed these monitoring and evaluation thresholds.

  Assuming an equilibrium factor of 0.4 and continuous occupancy, § 835.402(c)(3) requires an internal dose evaluation at 0.83 pCi/L above background for visitors. § 835.403(a)(1) requires air monitoring at 1.7 pCi/L above background. § 835.402(c)(1) requires internal dose evaluation at 1.7 pCi/L above background. These action levels are very close to ambient background levels of radon and in some cases would be indistinguishable from background. For comparison, the EPA (Marcinowski 1992, Marcinowski et al. 1994) reports that the average (arithmetic mean) radon concentration in U.S. houses is 1.25 pCi/L.

- Because of the low individual monitoring and evaluation thresholds (see above requirements), implementation of the status quo results in an increase in the number of monitored individuals and therefore exposure reports for members of the public (visitors) and radiological workers.

- The low posting threshold required by the status quo results in more areas being posted as Airborne Radioactivity Areas. The RadCon Manual frisking requirement on leaving an Airborne Radioactivity Area would slow exit from these areas, resulting in lost productivity.

  Performing individual frisking at an EEC 3.3 of pCi/L is not technically justified, since limiting the spread of contamination of the short-lived radon progeny is not a radiological concern at this level. 10 CFR 835 and the RadCon Manual require workplace areas with equilibrium equivalent radon and thoron concentrations (EECs) exceeding 3.3 pCi/L and 0.75 pCi/L, respectively, to be posted as airborne radioactivity areas. RadCon Manual Article 338 requires whole body frisking prior to exiting such areas.

A.2.2 Alternative 1: Use 10 CFR 835 with increased personnel and workplace monitoring thresholds

A. Technical discussion of Alternative 1

This alternative can be implemented by modifying 10 CFR 835 or by invoking the exemption process of 10 CFR 820. The DAC values for radon, thoron, and their progeny in 10 CFR 835 would remain the same. The threshold for personnel monitoring in 10 CFR 835.402(c) would be increased from 100 mrem CEDE to 500 mrem CEDE in one year. The threshold for workplace monitoring would be increased by changing "2% of an ALI" to "10% of an ALI" in 10 CFR 835.403(a)(1). This would amount to increasing the respective threshold values by a factor of 5.

B. Major Advantages

- This alternative significantly reduces the number of workers requiring personnel monitoring for radon or thoron.
- This alternative uses the same threshold for monitoring as the U. S. Nuclear Regulatory Commission's (NRC's) 10 CFR 20. In 1993 DOE stated, "Due to the unique and diverse activities conducted by the DOE, the Department has chosen to require individual whole body monitoring at levels lower than those required but the NRC (i.e., at 2% rather than 10% of the limit)" (Preamble to 10 CFR 835, 58 FR 65473, col. 2, 14 December 1993). However, due to the difficulty of distinguishing 2% of an ALI from background, 10% is a more appropriate level for radon or thoron monitoring under 10 CFR 835.402.
- Because the thresholds for monitoring and evaluating exposures to radon are higher than the status quo, proper characterization of background radon levels may not be that important at some DOE operations or sites. However, DOE guidance for characterizing background radon levels in the workplace is still required.

  With the increased threshold for personnel monitoring for radon, continuous occupancy, and an equilibrium factor of 0.4, § 835.402(c)(3) requires internal dose evaluation for visitors at 4.2 pCi/L above background. With the increased threshold for workplace monitoring, § 835.403(a)(1) requires air monitoring at 8.3 pCi/L above background. § 835.402(c)(1) requires internal dose evaluation at 8.3 pCi/L above background.

- Posting Airborne Radioactivity Areas and performing individual frisking at an EEC of 3.3 pCi/L (10% of a DAC) is not a major impact to most DOE facilities and sites. The threshold for posting and the threshold for internal dose evaluation with continuous occupancy are the same: 3.3 pCi/L EEC.

With this alternative, 10 CFR 835 and the RadCon Manual would require workplace areas with equilibrium equivalent radon and thoron concentrations (EECs) exceeding 3.3 pCi/L and 0.75 pCi/L, respectively, to be posted as airborne radioactivity areas. RadCon Manual Article 338 requires whole body frisking prior to exiting such areas.

C. Major Disadvantages

- The DOE would have to revise 10 CFR 835 and increase the personnel monitoring and workplace monitoring thresholds for radon and thoron by a factor of 5 and alter and add some definitions.

- New education and training is needed for general employees and radiological workers to cover increased monitoring thresholds and changed definition of radiological worker.

- If the definition of radiological worker as someone likely to be exposed to 0.1 rem TEDE is not changed, persons exposed to radon progeny between 0.08 WLM (100 mrem) and 0.4 WLM (500 mrem) would be considered to be radiological workers but would not be monitored. This may create confusion and discontent among workers who would perceive a "double standard" for radon and other radiation.

- The monitoring threshold (500 mrem) is the same as the administrative control level (500 mrem) for some DOE sites. This makes it impractically high for keeping doses below the administrative control level.

A.2.3 Alternative 2: Use 10 CFR 835 with revised DAC based on ICRP Publication 65

A. Technical discussion of Alternative 2

This alternative can be implemented by modifying 10 CFR 835 or by invoking the exemption process of 10 CFR 820. The requirements of 10 CFR 835 would remain the same except the DAC values for radon and thoron would be revised to be consistent with the recommendations of ICRP Publication 65 and the IAEA. This would amount to increasing the respective DAC values by a factor of 2.5. Footnotes for Appendix A of 10 CFR 835 would state that the DAC values for radon and thoron are based on information given in ICRP Publication 65 and IAEA Safety Series 115-I.

B. Major Advantages

- With adoption of the current DOE radiation protection standards and accepting a DAC value based on ICRP/IAEA recommendations, minimal revision of 10 CFR 835 or RadCon Manual would be needed.

- The DACs for radon and thoron based on ICRP/IAEA recommendations are consistent with the latest international guidance.

- No new education and training is needed for general employees and radiological workers, since the current dose reporting system is already covered in radiation protection training programs as specified in the RadCon Manual.

- Because the thresholds for monitoring and evaluating exposures to radon are higher than for the status quo, proper characterization of background radon levels may not be important at some DOE operations or sites. However, DOE guidance for characterizing background radon levels in the workplace is still required.

  With increased DACs for radon, continuous occupancy, and an equilibrium factor of 0.4, § 835.402(c)(3) requires internal dose evaluation for visitors at 2.1 pCi/L above background. § 835.403(a)(1) requires air monitoring at 4.2 pCi/L above background. § 835.402(c)(1) requires internal dose evaluation at 4.2 pCi/L above background.

- Compared to the status quo, posting Airborne Radioactivity Areas and performing individual frisking at an EEC of 8.3 pCi/L is not a major impact to most DOE facilities and sites.

  With an increased DAC value for radon and thoron, 10 CFR 835 and the RadCon Manual would require workplace areas with equilibrium equivalent radon and thoron concentrations (EECs) exceeding 8.3 pCi/L and 19 pCi/L, respectively, to be posted as airborne radioactivity areas. RadCon Manual Article 338 requires whole body frisking prior to exiting such areas.

C. Major Disadvantages

- The DOE would have to revise 10 CFR 835 and increase the DAC values for radon and thoron by a factor of 2.5 and alter and add some definitions.

- There is no consensus in the USA or in the DOE on adopting the 1994 ICRP/IAEA recommendations.

A.2.4 Other Alternatives

Other regulatory alternatives considered, evaluated, and dismissed by the Radon Subcommittee include:

- Using a "Total Radiation Exposure Index" (TREI) instead of total effective dose equivalent (TEDE). This approach limits the risk to the worker by requiring that the fraction of the worker's TEDE limit be combined with the fraction of the radon and thoron exposure limit. Using the TEDE limits in 10 CFR 835 and the ICRP Publication 32 exposure limits for radon (4 WLM) and thoron (12 WLM), the Total Radiation Exposure Index (TREI) can be defined:

$$\text{Total Radiation Exposure Index } (TREI) = \frac{TEDE}{5\text{ rems}} + \frac{E_{Rn}}{4\ WLM} + \frac{E_{Tn}}{12\ WLM},$$

where
TEDE denotes total effective dose equivalent in rems;
E_{Rn} denotes potential alpha energy exposure to radon progeny in WLM; and
E_{Tn} denotes potential alpha energy exposure to thoron progeny in WLM.

The Radon Subcommittee also considered using the ICRP 65 limits, where the TREI would be

$$\text{Total Radiation Exposure Index } (TREI) = \frac{TEDE}{5\text{ rems}} + \frac{E_{Rn}}{10\ WLM} + \frac{E_{Tn}}{30\ WLM},$$

Under the TREI approach, there are 3 worker limits or levels:

the DOE regulatory limit:	*TREI* <	1.0
the Administrative Control Level:	*TREI* <	0.4
the Lifetime Control Level:	*Cumulative TREI* <	0.2 × (age in years)

The major advantages of the TREI approach include:

- The use of a combined limitation system eliminates the need to convert a field exposure measurement to dose.

- Since no dose calculation is required, the tissue weighting factor is irrelevant.

  The use of any of the three currently used tissue weighting factors for radon progeny exposure of the lung (0.06, 0.08, 0.12) is not required. The calculation of CDE as specified in 10 CFR 835 would not be required.

The major disadvantages of the TREI approach include

- Significant revision of 10 CFR 835 and the RadCon Manual is required to incorporate the TREI concept.

  The current DACs published in 10 CFR 835 would remain intact. Both 10 CFR 835 and the RadCon Manual would require extensive revision. These documents would, however, have to be modified to specifically exempt radon and thoron progeny from being included in TEDE and to implement the TREI approach.

- Additional training is required to educate workers on the new dose limitation concept.

• Modifying 10 CFR 835 and the RadCon Manual to incorporate completely separate limits for radon, thoron, and their progeny, above and beyond the TEDE limits. The historical precedent for this approach is the system of ICRP Publication 2 (1959), in which internal doses were regulated separately from external doses. This would simplify compliance considerably, but would not result in the same degree of limitation of all radiological risks as other alternatives. It would also be out of step with the guidance of the ICRP and the NCRP, and with practices in other countries.

• Adopting a system in which radon, thoron, and their progeny were subjected to an OSHA type permissible exposure limit (PEL) which must not be exceeded. Such an approach is appropriate only for hazardous agents that produce biological effects above some threshold of exposure, but not below that threshold. The PEL approach was dismissed because the Radon Subcommittee recognized that it is not appropriate for limitation of risk of stochastic health effects, which requires an ALARA approach.

• Deregulating radon, thoron and their progeny completely by deleting the DACs from 10 CFR 835 and the RadCon Manual. This approach was dismissed as being irresponsible but is listed for completeness, since it has the advantage of simplifying regulatory compliance for sites with radon problems.

A.3 TECHNICAL DISCUSSION OF SELECTED TOPICS

A.3.1. Effective Dose Equivalent and Effective Dose: Essentially the Same for Radon and Thoron.

For dosimetry of radon and thoron progeny in the human respiratory tract, it has been shown (Birchall and James, 1994) that the older ICRP methods (ICRP Publications 26 and 30) yield essentially the same results as the newer ICRP methods (ICRP Publication 60). The tissue weighting factor for lung is 0.12 in both methods. The quality factor for alpha particles is unchanged from a value of 20, but has been renamed “radiation weighting factor” in ICRP Publication 60. Thus, distinguishing between effective dose equivalent (ICRP-26 & -30) and effective dose (ICRP-60) or any of the related dose quantities has no impact on the conclusions of this document. Also, throughout the document, any values from the literature in sieverts have been converted to rems.

Both DOE and NRC DACs are “5-rem” DACs (for all radionuclides with an “S” in the right-hand column of 10 CFR 835 Appendix A), meaning that exposure to 1 DAC for 2000 hours results in a committed effective dose equivalent of 5 rems. The most recent work of the ICRP and IAEA does not quote DACs at all, but rather give annual limits on exposure for radon and thoron (i.e., 10 and 30 WLM per year, respectively). Throughout this document, any reference to ICRP/IAEA "DACs" is based on *deriving* the PAEC or equilibrium equivalent concentration that, based on ICRP/IAEA recommendations, would result in 5 rems CEDE if breathed for 2000 hours.

A.3.2 10 CFR 835 Monitoring Thresholds

The change of DAC from the current one (based on ICRP Publication 32) to the new one (based on ICRP Publication 65) results in changes in monitoring thresholds. To properly compare the required monitoring thresholds to the measured radon concentrations presented in Figure 1, the monitoring thresholds need to be adjusted by the assumed equilibrium factor for radon (0.4). Using ICRP Publication 32 and an equilibrium factor of 0.4, the radon monitoring thresholds for visitors and workers are calculated to be 0.83 pCi/L and 1.7 pCi/L, respectively. Based on ICRP Publication 65 and assuming an equilibrium factor 0.4, the radon monitoring thresholds for visitors and workers are calculated to be 2.1 pCi/L and 4.2 pCi/L, respectively. As evidenced by Figure 1, the radon monitoring thresholds under 10 CFR 835 (based on ICRP Publication 32) fall within the normal fluctuations of background and the higher monitoring thresholds (based on ICRP Publication 65) fall above most of the normal fluctuations in background.

A.3.3 Radiological Control Technician Training Needs for Radon, Thoron, and Their Progeny

Training requirements for radiological control technicians in 10 CFR 835, the RadCon Manual, and the DOE Implementation Guide on training do not address the special quantities and units needed for measurements of radon and thoron and their short-lived progeny. As a minimum, technicians should receive training on the origin, nature, and radiological properties of radon and thoron and their short-lived progeny, what background levels are, the time behavior of these radioactive materials, and the quantities (and units) concentration (pCi/L), equilibrium equivalent concentration (pCi/L), potential alpha energy concentration (WL), potential alpha energy exposure (WLM), equilibrium factor (dimensionless), unattached fraction (dimensionless), and the measurement of these quantities.

A.3.4 Dose Equivalent Quantities and Dose Conversion Convention

The ICRP/IAEA dose conversion convention does not arise from computing committed effective dose equivalent per WLM in the traditional way, that is, from the standard values of absorbed dose to lung per WLM and using the tissue weighting factor. The ICRP's dose conversion convention (ICRP 1994) abandons the traditional relationship (used by DOE) between absorbed dose, quality factor, tissue weighting factor, and effective dose equivalent. For radon or thoron progeny, these relationships are

$$\begin{aligned} H_{lung,\,50} &= Q_{\alpha} D_{lung,\,50} = 20\, D_{lung,\,50}, \\ H_{E,\,50} &= w_{lung} H_{lung,\,50} = 0.12\, H_{lung,\,50} \end{aligned} \qquad \textbf{(3)}$$

where
$D_{lung,\,50}$ denotes the 50-year committed absorbed dose to the lung (rad or Gy);
Q_{alpha} denotes the quality factor for α radiation (20);
$H_{lung,\,50}$ denotes the 50-year committed dose equivalent to the lung (rem or Sv);
w_{lung} denotes the tissue weighting factor for the lung (w_{lung} = 0.12 in the DOE);
$H_{E,\,50}$ denotes the 50-year committed effective dose equivalent.

Use of the above equations with either the ICRP Task Group on Lung Dynamics respiratory tract model (ICRP 1966, ICRP 1979) or the new ICRP respiratory tract model (ICRP 1994b) results in a dose conversion convention on the order of 1.3 rems per WLM, as contrasted with the ICRP Publication 65 dose conversion convention of 0.5 rem per WLM (Birchall and James 1994). Thus, adopting the ICRP Publication 65 risk-based DACs results in a contradiction on the basis of the above equations if radon and thoron exposures are expressed in rems. Adopting a dose conversion convention for radon and thoron exposures in WLM avoids this contradiction by modifying definitions in 10 CFR 835.

A.3.5 Choices of Tissue Weighting Factor for Lung

There are two issues concerning the tissue weighting factor for the lung. First, using the direct conversion from PAEE in WLM to H_E, the conventional method of computing dose is bypassed: one is not using absorbed dose to the lung, the quality factor for alpha particles, and the tissue weighting factor for lung to arrive at H_E due to radon or thoron. Secondly, a tissue weighting factor for the lung is needed to compute $H_{T=lung}$ from the portion of H_E due to radon or thoron.

The ICRP Publication 26 weighting factor for the lung is 0.12, and has been adopted by EPA, NRC, and DOE; and, in most of its recent publications, by the NCRP. It is unchanged in the 1990 recommendations of the ICRP. In its Report No. 93, the NCRP inexplicably used a weighting factor of 0.08 for the lung in the context of radon and its short-lived progeny. In its 1981 Publication 32, on which DOE's 10 CFR 835 DACs for radon, thoron, and their short-lived progeny are based, ICRP used a "regional lung model," in which the weighting factor for the tracheobronchial (TB) region of the lung was 0.06 (virtually all of the dose produced by radon or thoron progeny is in the TB region).

The Radon Subcommittee endorses the continued use of w_{lung} = 0.12, as specified in 10 CFR 835.2(b).

A.3.6 The Radon Subcommittee's Policy on Dealing with Inconsistencies in Numerical Values Due to Roundoff Errors

To avoid contradictions in DACs and other action levels, the Radon Subcommittee decided to derive all radon and thoron concentration values from 10 CFR 835 Appendix A PAEC limits (or ICRP/IAEA PAEE limits for newer recommendations), rather than from 10 CFR 835 Appendix A equilibrium equivalent DACs, which give slightly different answers and lead to confusion.

Specifically, the equilibrium equivalent radon concentration associated with the 10 CFR 835 Appendix A PAEC DAC of 1/3 WL is $3.3\bar{3}$E-8 μCi/mL (where the bar denotes a continued decimal), while the current 10 CFR 835 equilibrium equivalent DAC is published as 3E-8 μCi/mL (due to DOE's policy choice of rounding DAC values to one "significant" figure). The two DOE values differ by 11%. Since both 1/3 WL and 3E-8 μCi/mL appear in Appendix A, it is unclear which value is to be used.

Similarly, the equilibrium equivalent concentration of thoron associated with 10 CFR 835 Appendix A's PAEC DAC of 1 WL is 7.46E-9 μCi/mL, while the equilibrium equivalent DAC listed next to radon-220 in Appendix A in 10 CFR 835 is 8E-9 μCi/mL, a difference of 7%.

These seemingly trivial differences lead to contradictions. Because all recent and past recommendations of the ICRP and IAEA for radon and thoron are given in PAEC or PAEE, the Radon Subcommittee has chosen to use only equilibrium equivalent DAC values derived from PAEC or PAEE, namely, $3.3\overline{3}$E-8 µCi/mL for radon and 7.46E-9 µCi/mL for thoron. For the equilibrium equivalent DACs derived from the newer ICRP/IAEA recommendations, the Subcommittee has chosen to use $8.3\overline{3}$E-8 µCi/mL for radon and 1.87E-8 µCi/mL for thoron.

To avoid injecting bias and contradictions into its recommendations, the Subcommittee has used exact fractions (e.g., 1/3 WL, 5/6 WL; 1/6 rem/WLM, 5/12 rem/WLM; 1/600 Sv/WLM, and 5/1200 Sv/WLM), have been used where appropriate.

A.3.7 Equilibrium Equivalent DACs and Ambient DACs

Measurements of radon or thoron concentrations made in the field must either be converted to equilibrium equivalent concentrations for comparison with equilibrium equivalent DACs, or compared directly to "ambient" DACs that have been adjusted by the equilibrium factor. An ambient DAC is simply the equilibrium equivalent DAC divided by the equilibrium factor. The ambient DAC is thus different for each different equilibrium factor. For example, for an outdoor site where the radon equilibrium factor was known never to exceed 0.2, the site-specific ambient DAC for radon would be 416 pCi/L (= 83.3 pCi/L ÷ 0.2). This value would be used for direct comparison with results of field measurements.

A.4 Appendix A References

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APPENDIX B: INTERNATIONAL STRATEGIES FOR PROTECTION AGAINST WORKPLACE RADON EXPOSURE

B.1 Canada

- Current status: Workers who do not have a "reasonable" probability of receiving > 5 mSv/y while working under the auspices of an AECB licensee are not considered as atomic radiation workers (ARW).

- Proposed status: Workers who do not have a "reasonable" probability of receiving > 1 mSv/y while working under the auspices of an AECB licensee will not be considered as atomic radiation workers (ARW).

- Inclusion of radon-and-thoron-daughter exposures and intakes of other radioactive material in the aggregate effective dose is accomplished by a "combining formula":

$$\frac{\text{External Dose}}{20\ mSv} + \frac{\text{Radon Daughter Intake}}{4.7\ WLM} + \frac{\text{Thoron Daughter Intake}}{14.1\ WLM} + \frac{\text{Radioactive Dust Intake}}{ALI\,(20\ mSv)} \leq 1$$

- The denominators in the combining formula represent the individual annual limits on external dose, radon progeny exposure, thoron progeny exposure, and the annual limits on intake (ALIs) of other radioactive materials, as given in ICRP Publication 61.

- The minimum level at which personal monitoring of radon-daughter exposure will be required is thus approximately 1.2 WLM/y, and that for personal monitoring of thoron progeny approximately 3.6 WLM/y.

B.2 Australia

- Control of radon and thoron will be required in two categories of workplace: (I) those requiring the application of the system of radiation protection (e.g., uranium mines), and (II) others where the radon gas concentration exceeds an "Action Level" of 1000 Bq/m^3.

- In category I workplaces, all radon [and/or thoron] exposures will be assessed and counted as occupational exposures, whether the radon concentration is above 1000 Bq/m^3 or not.

- In category II workplaces, if intervention to reduce the radon gas concentration below 1000 Bq/m^3 is unsuccessful or impracticable, then the system of radiation protection will apply and thus doses from radon exposure in the workplace will need to be assessed and counted as occupational exposure.

- Assuming an equilibrium factor, F, of 0.4, then a radon gas concentration of 1000 Bq/m^3 would correspond to a radon daughter concentration of approximately 0.11 WL, and an annual exposure of approximately 1.3 WLM.

B.3 South Africa

- Proposed strategy to control radon exposure in workplaces that is similar to the Australian proposal: except that the "Action Level" will be set at 400 Bq/m^3 radon gas concentration.

- This "Action Level" will correspond to a radon daughter concentration of approximately 0.04 WL, and an annual exposure of approximately 0.5 WLM. This is approximately one-tenth of the annual limit on exposure (ALE) for radon daughters (averaged over 5 years) recommended in ICRP Publication 65.

B.4 United Kingdom

- If the radon gas concentration in any workplace is deemed to be less than 400 Bq/m^3, then no monitoring of the actual radon exposure nor recording of the effective dose will be required.

- If the radon gas concentration in a workplace is deemed to exceed 400 Bq/m^3, then individual worker's exposures to radon [and presumably also thoron] decay products will have to be monitored and recorded in the same way as other sources of exposure.

- Monitored radon exposures are expected to be entered into the aggregated annual effective dose according to the ICRP Publication 65 "dose conversion convention" of 4 WLM/y $\equiv$ 20 mSv/y.

B.5 France

- The French use a sum-of-fractions quantity (dimensionless) called the TET which is expressed as

$$TET = \frac{E_{external}}{50\ \text{mSv}} + \sum_i \frac{I_i}{ALI_i} ,$$

where
E is the external dose equivalent in mSv;
I_i is the intake (or "exposure") of the ith agent; and
ALI_i is the annual limit on "exposure" or intake of the ith agent.

- The limits on intake for radon and thoron progeny are expressed as potential alpha energy (PAE) expressed in joules (J), following the practice in ICRP Publication 32. These limits in France are 2.5× lower than the newly-recommended levels in ICRP Publication 65.