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RELATIVE HAZARD OF THE VARIOUS
RADIOACTIVE MATERIALS*

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Abstract

An equation is given for the relative hazard, H , of various radionuclides under uniform working conditions. H is defined as the ratio of the average $\mu\text{c/cc}$ inhaled in the working area to the maximum permissible concentration, MPC, of the radionuclide for occupational exposure. The variation of H is discussed in relation to such parameters as radioactive and biological half lives of the radionuclides, fractional retention, dilution factors, specific activity, energy, RBE, relative damage factor, n , mass of the critical organ and the maximum permissible dose to the critical organ. Comparisons are made with values of H obtained by this and other investigations. The values of H obtained by this method appear to be consistent with estimates from operational experience. A table of values of specific activity, $(\text{MPC})_c$ and relative hazard, H , are given for the radionuclides listed in ICRP Publication No. 2, plus values for a number of additional transuranic elements not previously listed by the ICRP.

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Introduction

At the first conference on the Peaceful Uses of Atomic Energy,¹ formulae were given for determining the relative hazard, H , of work with the various radionuclides. It was pointed out that H could be expressed as,

$$H = \frac{P}{MPI} \quad (1)$$

in which P was the probability of taking a certain quantity of the radionuclide into the body and MPI was the maximum permissible daily intake into the body given in $\mu\text{c/day}$. It was assumed that the dust loading of air in areas where work was being done with radioactive material would not exceed the dust loading in the air of the average city. Drinker and Hatch² had shown that this corresponds to 0.1 to 1 mg/m^3 or 1 to 10 mg of dust inhaled per eight-hour work day. It was noted also at that time that the average shipment of radionuclides from Oak Ridge National Laboratory was 100 mc (excluding the large radiotherapy sources of Co^{60}); so, for convenience, it was assumed that the average accident involved work with 100 mc . The relative hazard associated with work involving 100 mc of various radionuclides was given by the equation,

$$H = \frac{10}{(MPI) \times (\text{mg}/100 \text{ mc})} = \frac{0.1}{(MPC)_c \times D \times (\text{mg}/\text{mc})} \quad (2)$$

in which $(MPC)_c$ = maximum permissible concentration ($\mu\text{c}/\text{cc}$) in the medium (air, water, food), D = daily intake of medium (cc/day), $10/(\text{mg}/100 \text{ mc})$ or $0.1/(\text{mg}/\text{mc})$ was the probability, P , of inhalation of a given quantity of the radionuclide so that when $\text{mg}/\text{mc} \leq 0.1$, P was set equal to 1. Similar assumptions were made relative to the contamination of a wound, and values of H were found for all the radionuclides for which MPC values had been published at that time by the ICRP and the NCRP.

More recently, a number of investigators have attempted to develop mathematical relationships which can be used to determine the relative hazard, H ,

of radionuclides. Perhaps the most successful effort was by Duhamel and Lavie,³ who suggested the relation,

$$H = \frac{1}{\sqrt{(MPC)_g \times (MPC)_c}} \quad (3)$$

where $(MPC)_g$ = maximum permissible concentration of the material in $\mu\text{g}/\text{cc}$ and $(MPC)_c$ = maximum permissible concentration of the material in $\mu\text{c}/\text{cc}$. * This equation can be written in the form,

$$H = \frac{\sqrt{c/g}}{(MPC)_c} \quad (4)$$

in which c/g is the specific activity of the radionuclide in curies/g.

Heuristic Interpretation of the Relative Hazard Formula

In this paper, equation 2 of Morgan et al¹ has been restated as

$$H = C \times \text{Min} (A \times c/g, 2.9 \times 10^{-10}) / (MPC)_c \quad (5)$$

in which the dimensionless index H is the relative hazard from work with a given number C of curies of a radioactive material. The symbol $\text{Min} (x, y)$ denotes the smaller of x and y . Thus, $\text{Min} (A \times c/g, 2.9 \times 10^{-10}) = A \times c/g$ if $A \times c/g \leq 2.9 \times 10^{-10}$ but $\text{Min} (A \times c/g, 2.9 \times 10^{-10}) = 2.9 \times 10^{-10}$ if $A \times c/g > 2.9 \times 10^{-10}$. This equation is derived below as the ratio of the amount (μc) of the radionuclide taken into the body per cc of inhaled air in the work area during a hypothetical incident to the maximum permissible concentration (MPC) of the radionuclide in air ($\mu\text{c}/\text{cc}$) for occupational exposure. The constant, A , is equal to the dust loading in the air ($\mu\text{g}/\text{cc}$) divided by the dilution factors $(b + 1)(d + 1)$. It is given by the equation,

$$A = \frac{10^{-4}}{(d + 1)(b + 1)} \quad (6)$$

*Strictly, symbols $(MPC)_{a,g}$ and $(MPC)_{a,c}$ denoting the maximum permissible concentration in air in $\mu\text{g}/\text{cc}$ and $\mu\text{c}/\text{cc}$, respectively, should be used but since only $(MPC)_a$ values are used throughout this paper, the subscript "a" is omitted in order to simplify the notation.

in which the dust loading is assumed to be at a constant (or average) level of 10^{-4} $\mu\text{g}/\text{cc}$; b is the chemical dilution of the radioelement by stable isotopes of the radioelement or by other inert material (i. e., the chemical dilution of the radionuclide by stable material in the mixture and escaping into the work area); d is the dilution of the escaping radioactive mixture by airborne floor dust. The function $\text{Min}(A \times c/\text{g}, 2.9 \times 10^{-10})$ imposes a restriction on the air activity ($\mu\text{c}/\text{cc}$) in conformity with the assumption that the air activity in the working area will not be permitted appreciably above 10 times the MPC for Ra^{226} or above the MPC for Sr^{90} .

For convenience in this comparison, Ra^{226} is taken as the reference standard, i. e., the relative hazard, H , in equation 5 is set equal to 1 for Ra^{226} . This is done because for many years Ra^{226} has been the standard of comparison for determining the $(\text{MPC})_c$ values for bone-seeking radionuclides and it is the only radionuclide for which man has had over 60 years of recorded exposure history and, in some cases, a rather extensive evaluation of the consequent damage. When equation 5 is normalized to Ra^{226} for which $(\text{MPC})_c = 2.9 \times 10^{-11}$ $\mu\text{c}/\text{cc}$ for occupational exposure 40 hours per week and for which the specific activity $c/\text{g} = 0.981$, the constant $A = 2.9 \times 10^{-11}$ and the constant dilution factors $(b + 1)(d + 1) = 3.43 \times 10^6$. If equation 5 had been normalized to Pu^{239} , $(b + 1)(d + 1)$ would have been equal to 3.56×10^6 . Thus, in view of the fact that the limited accuracy of the biological data used in the Internal Dose Handbooks of NCRP and ICRP has not warranted the listing of MPC values of radionuclides to more than one significant figure, both isotopes -- Ra^{226} and Pu^{239} -- may be considered as reference standards for which H is equal to 1.

Equation 5 is intended to represent the hazard of rather routine day-to-day work with a radioactive material. It is not intended to represent the hazard of a major explosion or of a large, sudden release of radioactive material into the environment, although with certain additional assumptions relative to the amount of energy dissipated in an explosion and the amount of material released, equation 5 might be appropriately modified and extended to include such events. This equation is intended to express the hazard of routine work with any radionuclide in reference

to similar work with Ra^{226} using comparable facilities and procedures. Values of H obtained from equation 5 are intended to indicate the level of precautionary measures that should be taken for work with a radionuclide; for example, the type of chemical hood needed, the air changes required, the filters that are recommended in the ventilation system, the kinds of covering that are appropriate for the floor and table tops, the safety measures that should be enforced, etc.

Derivation of the Relative Hazard Formula

In deriving equation 5, six assumptions are made as follows:

- (1) The relative hazard, H is proportional to the ratio of the intake by the worker to the $(\text{MPC})_c$ of the radionuclide or since the intake is assumed to be proportional to the average concentration in laboratory air, H is the ratio of the $\mu\text{c}/\text{cc}$ of laboratory air to the $(\text{MPC})_c$ of the radionuclide. Thus,

$$H = \frac{\mu\text{c}/\text{cc}}{(\text{MPC})_c} \quad (7)$$

The symbol $(\text{MPC})_c$ will be used to denote the maximum permissible concentration in air for occupational exposure (40 hours a week) in units of $\mu\text{c}/\text{cc}$ of air.

- (2) The relative hazard $H = 1$ for Ra^{226} under standard conditions of dilution specified below.
- (3) The activity ($\mu\text{c}/\text{cc}$) in the laboratory air is monitored continuously or rather frequently and is not permitted to exceed for significant periods 10 times the MPC for Ra^{226} ($2.86 \times 10^{-10} \mu\text{c}/\text{cc}$) or, what is essentially the same value, the MPC for Sr^{90} ($2.89 \times 10^{-10} \mu\text{c}/\text{cc}$). This is a level that is easily monitored by fixed or portable air monitoring equipment and it is assumed that should such a level be exceeded, remedial measures would be taken immediately to restore better working conditions. From this assumption,

$$H \leq \frac{10(\text{MPC})\text{Ra}^{226}}{(\text{MPC})_c} \text{ or } \frac{2.86 \times 10^{-10}}{(\text{MPC})_c} \text{ and } H \leq \frac{(\text{MPC})\text{Sr}^{90}}{(\text{MPC})_c} \text{ or } \frac{2.89 \times 10^{-10}}{(\text{MPC})_c} \quad (8)$$

- (4) The loading of dust and airborne escaping material in the laboratory air is constant at the value 10^{-4} $\mu\text{g}/\text{cc}$. That is,

$$(\mu\text{g})_D/\text{cc} = (\mu\text{g})_F/\text{cc} + (\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc} = 10^{-4} \quad (9)$$

in which $(\mu\text{g})_D/\text{cc} = \mu\text{g}$ of dust and airborne material/cc of laboratory air, $(\mu\text{g})_F/\text{cc} = \mu\text{g}$ of floor dust (lint, smoke, sand, etc.)/cc of laboratory air, $(\mu\text{g})_E/\text{cc} = \mu\text{g}$ of inert material escaping with radionuclide/cc of laboratory air, and $(\mu\text{g})_R/\text{cc} = \mu\text{g}$ of undiluted radionuclide/cc of laboratory air.

- (5) It is assumed that the material as it escapes initially into the laboratory is a representative sample of the mixture before it escaped, i. e., the ratio of radioactive material to inert material in the escaping air equals the ratio of these materials in the original mixture or compound. Thus, the chemical and isotopic dilution factor is $(b + 1)$ in which,

$$(b + 1) = \frac{(\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc}}{(\mu\text{g})_R/\text{cc}} \quad (10)$$

This assumption may not be correct in cases where there can be fractionation of certain of the chemicals as they escape. Therefore, where specific data are available, a correction for this fractionation should be applied to the value of b in obtaining H for a particular chemical operation.

- (6) The amount of floor dust $(\mu\text{g})_F/\text{cc}$ that becomes airborne is a constant multiple d of the amount of airborne material escaping into the laboratory for a given operation involving work with radionuclides for which the ratio of mass to activity is high, i. e., $(\text{c/g})_R \leq 10 \mu\text{c}/\mu\text{g}$. This assumption states that when the work involves 0.1 or more grams of radionuclide per curie, the ratio of $\mu\text{g}/\text{cc}$ of floor dust becoming

airborne to the $\mu\text{g}/\text{cc}$ of escaping material is relatively constant.

Thus, the dust dilution factor is $(d + 1)$ in which,

$$(d + 1) = \frac{(\mu\text{g})_F/\text{cc} + (\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc}}{(\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc}} = \frac{(\mu\text{g})_D/\text{cc}}{(\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc}} \quad (11)$$

The total dilution factor $(b + 1)(d + 1)$ is

$$(b + 1)(d + 1) = \frac{(\mu\text{g})_F/\text{cc} + (\mu\text{g})_E/\text{cc} + (\mu\text{g})_R/\text{cc}}{(\mu\text{g})_R/\text{cc}} =$$

$$\frac{(\mu\text{g})_D/\text{cc}}{(\mu\text{g})_R/\text{cc}} = \frac{10^{-4}}{(\mu\text{g})_R/\text{cc}} \quad (12)$$

From equations 7 -12, the general equation for H can be written as

$$H = \frac{\mu\text{c}/\text{cc}}{(\text{MPC})_c} = \frac{(\mu\text{g})_R/\text{cc} \times (\text{c/g})}{(\text{MPC})_c} = \frac{10^{-4} (\text{c/g})}{(b + 1)(d + 1)(\text{MPC})_c}$$

$$\text{but} \leq \frac{2.9 \times 10^{-10}}{(\text{MPC})_c} \quad (13)$$

In any case, it is assumed the concentration in the air being breathed will not rise above $2.9 \times 10^{-10} \mu\text{c}/\text{cc}$ because of remedial measures, including a possible alarm followed by the use of masks, the evacuation of personnel, etc. The formulae for H can be combined into a single formula by the use of the mathematical symbol $\text{Min}(x, y) =$ the smaller of x and y. Using this symbol, equation 13 can be rewritten as

$$H = \frac{\text{Min} \left(\frac{10^{-4} (\text{c/g})}{(b + 1)(d + 1)}, 2.9 \times 10^{-10} \right)}{(\text{MPC})_c} \quad (13a)$$

If H is normalized to equal 1 for the case of one curie of Ra^{226} , then

$$H = 1 = \frac{10^{-4} (0.981)}{(b + 1)(d + 1) 2.86 \times 10^{-11}}$$

$$\text{or } (b + 1)(d + 1) = 3.43 \times 10^6 \quad (14)$$

If, as a first approximation, the values of b and d for Ra^{226} are applied to work with other radionuclides in finding the relative hazard, H , then

$$H = \frac{2.92 \times 10^{-11} (c/g)}{(MPC)_c} \text{ but } H \leq \frac{2.9 \times 10^{-10}}{(MPC)_c} \quad (15)$$

Using the same notation as in equation 13a, these formulae can be combined to give

$$H = \frac{\text{Min} (2.92 \times 10^{-11} (c/g), 2.9 \times 10^{-10})}{(MPC)_c} = \frac{2.9 \times 10^{-11} \text{Min} (c/g, 10)}{(MPC)_c} \quad (15a)$$

This equation is the same as equation 5 if $A = 2.92 \times 10^{-11}$. It can also be written as

$$H = \frac{2.92 \times 10^{-11} \phi (c/g)}{(MPC)_c} \quad (15b)$$

where the function $\phi (c/g) = c/g$ if $c/g \leq 10$ and $\phi (c/g) = 10$ if $c/g > 10$.

Discussion of the Formula

The value of b is determined by the chemistry of the operation and the isotopic dilution and d is related to the amount of floor dust permitted in the working area, the size distribution of the dust particles and the air flow pattern which, in turn, determines the effective dilution of the radioactive material from the time it escapes into the working area until it is inhaled. It is of interest to note that the relative hazard H can be decreased directly by increases in the chemical and isotopic dilution factor, the dust dilution factor, or the product of these factors. Experimental values of this product $(b + 1)(d + 1)$ were not available to the writers for different chemical and engineering operations with the various radionuclides; so, in this paper, it was set equal to 3.43×10^6 for each of the radionuclides. Values of the product can and should be determined experimentally for many types of operations

with various chemical compounds and physical forms of the radioisotopes and for various working conditions. When such experimental data become available, more realistic and directly applicable values of H can be determined -- values that are applicable to the many chemical and physical forms of the radionuclides and to the various working conditions (i. e., values that are applicable to the equipment used, types of enclosure, dust level, etc.). However, in calculating such values of H , it must be kept in mind that the MPC values for radionuclides now available in the ICRP⁴ and NCRP⁵ publications are applicable only to the more common soluble and insoluble chemical forms of the radioelements and specific values of MPC must also be determined eventually for each chemical and physical form of the radionuclides in order to obtain the most reliable and applicable values of H from equation 13.

The boundary conditions imposed by equations 5 or 15 are tantamount to assuming the intake in μc is proportional to the concentration of activity in the air provided this activity does not exceed 2.9×10^{-10} and, under the assumption that the total load of airborne material does not exceed $10^{-4} \mu\text{g/cc}$, and for the dilution factors given, this will be realized if the specific activity does not exceed 10. For radionuclides of high specific activity, i. e., $\text{c/g} > 10$, the intake is assumed to be limited by an alarm or other monitoring device and subsequent action. This, of course, does not specify the specific activity of an individual dust particle since many dust particles would be relatively uncontaminated while others would have a specific activity much greater than that of the average. It is to be noted that when the dilution factor has a different value than that assumed here, the cut-off point in equation 15b which limits the concentration of the radionuclide in the intake air to not more than $2.9 \times 10^{-10} \mu\text{c/cc}$ will be different.

The value of $10^{-4} \mu\text{g/cc}$ (or 0.1 mg/m^3) used in this paper for the average dust loading in the air of the work area is probably not an unrealistic value, although there may be considerable variation in this value due to the differences in support of adequate measures for radiation protection to be found among the various organizations working with radionuclides. In general, however, the common use of good air filtering

systems in laboratories and production facilities where work is done with radioactive materials tends to keep the dust load of the air within an order of magnitude of this value. D. M. Davis and W. D. Cottrell⁶ made measurements from a number of dust samples collected in the isotope work areas of Oak Ridge National Laboratory and obtained a minimum value of $0.27 \times 10^{-4} \mu\text{g/cc}$, a maximum value of $1.8 \times 10^{-4} \mu\text{g/cc}$ or an average value of $0.86 \times 10^{-4} \mu\text{g/cc}$. The assumption that the air which is breathed in the working area has an average value of 100% of the MPC, in the case of Ra^{226} , or that $H = 1$ for Ra^{226} , is an arbitrary choice used only for convenient reference. The use of the same value of the product $(b + 1)(d + 1)$ in the calculation of all values of H in this paper was an expediency dictated by the lack of experimental data. When experimental values of the chemical, isotopic and dust dilution factors become available for the various physical and chemical forms of the radioisotopes and for various chemical and engineering operations, the values of H tabulated in this paper can be extended and improved by adjusting them appropriately. For the present, however, and until experimental data are available for such refinements in the calculations, the values of H given in this report should be considered primarily as the relative hazards (or risks) of occupational workers being exposed while conducting routine operations with one curie of the various radionuclides under operating conditions similar to those provided for Ra^{226} . Values of MPC (or $\mu\text{c/cc}$) rather than MPI (or $\mu\text{c/day}$) are used in equations given in this paper because of the convenience to the reader in applying values of MPC to be found in publications of ICRP⁴ and NCRP⁵. Other than mentioned above, the authors know of no good basis for these assumptions except that they lead to values of H that agree with years of laboratory experience.

The preceding heuristic derivation of H assumed one curie of activity to be present. When more than one curie of activity is involved in an operation, H increases proportionately according to equation 5. This assumption may be unjustified in some cases, and a closer investigation of this assumption might indicate that the cut-off value should vary somewhat according to the amount of activity involved. However, a large variation in amount of activity will often require changes in the

equipment and procedures which might affect the value of the dilution factors or make the operation not comparable with the previous operation. It would seem that the use of the curie amount as a multiplicative factor is probably conservative so far as the use of large activities is concerned. All the illustrative graphs and tables which follow are computed for the case of one curie of activity.

Comparison With Other Relative Hazard Formulae

In order to compare results, $\sqrt{c/g}$ from equation 4 of Duhamel and Lavie and $\phi(c/g)$ from equation 15b of this paper are plotted in Fig. 1. Also, values of H for typical radionuclides were determined by means of these two equations and plotted in this same figure. As would be expected, the two equations yield very similar values (within an order of magnitude) in the range from $c/g = 10^{-2}$ to 10^4 but are divergent beyond these limits. Thus, the authors' method (equation 15b) differs significantly from that of Duhamel and Lavie in that long-lived radionuclides, i. e., $c/g < 10^{-2}$, and the short-lived radionuclides, i. e., $c/g > 10^4$, are considered to be less hazardous.

Some typical values of H obtained by the use of these two equations (i. e., equation 4 normalized by the constant $A = 2.92 \times 10^{-11}$ and equation 15b) are plotted in Table I for ease of comparison. Both equations class Pu^{238} , Ac^{227} , Cf^{254} , 250, 249, Am^{242m} and Th^{228} as the most hazardous radionuclides. Also, both equations list radionuclides such as Ra^{226} , 228, Pu^{239} , 240, 241, Am^{241} , 243, U^{230} , 232, Pb^{210} , Po^{210} , Cm^{242} , 245, Sr^{90} and Th^{230} as very hazardous radionuclides. Both equations list radionuclides of extremely long half life such as In^{115} , Nd^{144} , Re^{187} , Rb^{87} as the least hazardous. Between these two extremes, the other radionuclides are classed by the two equations with varying degrees of intermediate hazard. There is, apparently, a weakness in the use of equation 4 in that H becomes too large as the half life of the radionuclide approaches zero.

Although it has not been possible to provide a strong theoretical basis, either for equation 4 or for equation 15b, a detailed comparison of the classification of various radionuclides obtained by the two equations with the classification arrived at through years of laboratory experience is useful in indicating the reliability of

FIG.1 COMPARISON OF VALUES OF RELATIVE HAZARD H AS OBTAINED
BY METHODS OF DUHAMEL AND LAVIE AND OF MORGAN et al.

TABLE-1

COMPARISON OF VALUES OF H OBTAINED BY METHODS OF
DUHAMEL AND LAVIE AND OF MORGAN SNYDER AND FORD

the two methods. This is the case because the only purpose in such equations is to provide a mathematical expression which can be shown to list the more common radionuclides in the known order of radiation hazard, as has been determined by experience, in the hope that this same equation may be relied upon as a guide to the relative hazard for work with a less common radionuclide where very little or no experience has been accumulated. Such classification of a radionuclide is required in order to determine the adequacy of health physics protective measures, waste disposal requirements, exempt quantities, shipping regulations, etc., for the various radioactive materials.

The greater the slope of the connecting lines plotted in Table I, the greater the difference in relative hazard as determined by the two methods. In general, and as would be expected from values plotted in Fig. 1, the majority of values of H obtained from equation 15b are less than those obtained from equation 4 when both equations are normalized by the same constant. However, this is considered to be of minor significance since the factor of primary interest is the ordering of the radionuclides and not the absolute magnitude of the relative hazard H . Table II provides, by the use of equations 4 and 15b, a comparison of the ordering of some of the more commonly used radionuclides and, in each case, this ordering is compared with that arrived at from laboratory experience. Perhaps such a comparison tends to justify the conclusion that equation 15b furnishes a relatively reliable means of classifying the radionuclides in the order of increasing radiation hazard and that this classification, in general, is in agreement with laboratory and industrial experience with these radionuclides. Undoubtedly, this ordering could be improved upon if specific values of the chemical, isotopic and dust dilution factors, i. e., $(b+1)(d+1)$, were available for each chemical and engineering operation with the various radionuclides and if values of $(MPC)_c$ were available for specific chemical forms of the radionuclides.

The general value of $(MPC)_c$ may be obtained from the handbooks on internal dose of the ICRP⁴ and NCRP⁵ and substituted in equations 5 or 13a to give the relation,

TABLE II

COMPARISON OF VALUES OF RELATIVE HAZARD OBTAINED
BY METHOD OF DUHAMEL AND LAVIE (EQUATION 4) AND
METHOD OF MORGAN, SNYDER AND FORD (EQUATION 15b)

Comparison	Comments
Ra ²²⁶ , Sr ⁹⁰ , Pu ²³⁹ and Po ²¹⁰ are considered to be very hazardous and of about equal hazard	Confirmed both by eq. 4 and eq. 15b
Pu ²³⁸ , Ac ²²⁷ , Cf ^{254, 250, 249} , Am ^{242m} and Th ²²⁸ are probably among the most hazardous radionuclides known	Confirmed both by eq. 4 and eq. 15b
Radionuclides such as Ra ^{226, 228} , Pu ^{239, 240, 241} , Am ^{241, 243} , U ^{230, 232} , Pb ²¹⁰ , Po ²¹⁰ , Cm ^{242, 245} , Sr ⁹⁰ and Th ²³⁰ are very hazardous	Confirmed both by eq. 4 and eq. 15b
Long-lived radionuclides such as Na ¹⁴⁴ , Re ¹⁸⁷ and Rb ⁸⁷ are among the least hazardous radionuclides	Confirmed both by eq. 4 and eq. 15b
I ¹³¹ is probably about the same hazard as Co ⁶⁰ and much less hazardous than Ra ²²⁶ or Sr ⁹⁰	Confirmed by eq. 15b but eq. 4 places I ¹³¹ equally hazardous to Sr ⁹⁰ and Ra ²²⁶ and much more hazardous than Co ⁶⁰
Sr ⁸⁹ and Ca ⁴⁵ are probably more hazardous than P ³²	Confirmed by eq. 15b but eq. 4 places P ³² more hazardous than Sr ⁸⁹ and Ca ⁴⁵
U ²³² with a half life of 74 years is probably more hazardous than U ²³⁰ with a half life of 21 days	Confirmed by eq. 15b but not confirmed by eq. 4
Th ²³⁰ with a half life of 8×10^4 years is probably less hazardous than Sr ⁹⁰ and Ra ²²⁶	Confirmed by eq. 15b but not confirmed by eq. 4
Xe ¹³⁵ is probably much less hazardous than Cs ¹³⁷ , U ^{233, 234}	Confirmed by eq. 15b but not confirmed by eq. 4
H ³ and C ¹⁴ are probably about equally hazardous	Confirmed by eq. 15b but not confirmed by eq. 4
Sm ¹⁴⁷ with a half life of 1.3×10^{11} years is probably much less hazardous than C ¹⁴	Confirmed by eq. 15b but not confirmed by eq. 4
H ³ is probably much more hazardous than U ²³⁸ and Th ²³²	Confirmed by eq. 15b but not confirmed by eq. 4
C ¹⁴ is probably more hazardous than U ²³⁵ and U ²³⁸	Confirmed by eq. 15b but not confirmed by eq. 4
Na ²⁴ with a half life of 15 hours is probably less hazardous than Ca ⁴⁵ , Co ⁶⁰ , Cs ¹³⁷ , Np ²³⁷ and Sr ⁸⁹	Confirmed by eq. 15b but not confirmed by eq. 4
Rn ²²² is probably less hazardous than Sr ⁸⁹ , Co ⁶⁰ , Ru ¹⁰⁶ and Cs ¹³⁷	Confirmed by eq. 15b but not confirmed by eq. 4
Rn ²²⁰ is probably much less hazardous than Pu ²³⁹ , Am ²⁴³ , Pb ²¹⁰ , Sr ⁹⁰ , Ra ²²⁶ , etc.	Confirmed by eq. 15b but not confirmed by eq. 4

$$H = \frac{6.8 \times 10^{13} \text{ CTf}_a (1 - e^{-0.693t/T}) \Sigma E(\text{RBE})n \text{ Min} \left[\frac{10^{-4} (c/g)}{(b+1)(d+1)}, 2.9 \times 10^{-10} \right]}{mR} \quad (15)$$

in which f_a = fraction of the radioactive material inhaled that is deposited in the critical body organ, m = mass of critical body organ (g), t = period of occupational exposure (years), T = effective half life (years), R = maximum permissible dose rate (rem/yr) delivered to the critical body organ, E = energy per disintegration (Mev) deposited in the critical body organ, RBE = relative biological effectiveness of the radiation, n = relative damage factor, $\text{Min} \left(\frac{10^{-4} (c/g)}{(b+1)(d+1)}, 2.9 \times 10^{-10} \right)$ has values as indicated for equation 5 and $10^{-4}/(b+1)(d+1)$ is a term that can be used if the chemical, isotopic and dust dilution factors are known (otherwise, it is set equal to 2.9×10^{-11}). Thus, it can be seen from equation 16 that, in general, and, as expected, the hazard H in the case of inhalation exposure increases directly with f_a , the fraction of the inhaled dust that arrives in the critical organ, with E , the energy delivered to the critical organ per disintegration, with the RBE of the radiation, and with n the relative damage factor. It decreases with m , the mass of the critical organ in which the radionuclide deposits and dilutes some or all of its energy of radioactive decay; it decreases with the constant dilution factors $(b+1)(d+1)$ until the concentration of the air in the working area reaches a level of $2.9 \times 10^{-10} \mu\text{c/cc}$. A comparison of ^{131}I which localizes primarily in the thyroid, with Pu^{239} which localizes primarily in the bone, and with H^3 which is rather uniformly distributed in the body, will illustrate the wide variation of these factors and the importance of them in determining the relative hazard H . Thus, $f_a \Sigma E(\text{RBE})n/mR = 0.23 \times 0.23(1)/(20 \times 30) = 8.8 \times 10^{-5}$ for ^{131}I ; $f_a \Sigma E(\text{RBE})n/mR = 0.2 \times 5.4(10)/5/(7 \times 10^3 \times 30) = 2.6 \times 10^{-4}$ for Pu^{239} and $f_a \Sigma E(\text{RBE})n/mR = 1 \times 0.006(1.7)/(7 \times 10^4 \times 5) = 2.9 \times 10^{-8}$ for H^3 .

The variation of the relative hazard H with the effective half life, T , is somewhat involved because T is a function of the radioactive half life, T_r , and of the biological half life, T_b , as indicated by the equation,

$$T = \frac{T_r T_b}{T_r + T_b} \quad (17)$$

Also, T_r is present in the formulae through the specific activity

$$c/g = \frac{3.56 \times 10^5}{W T_r} \quad (18)$$

In this equation, T_r is the radioactive half life in years and W is the atomic weight of the radionuclide. If equations 17 and 18 are substituted in equation 16 and, if for convenience in observing the behavior of H with respect to T_b and T_r , the dilution factors are specified as previously, i. e., $(b+1)(d+1) = 3.4 \times 10^6$, then equation 16 becomes

$$H = \left[\frac{2 \times 10^3 f_a \Sigma E(RBE)n}{mR} \right] T \left(1 - e^{-\frac{0.693t}{T}} \right) \phi (c/g)$$

where the bracketed factors do not involve T_r . Neglecting the bracketed factors, for the purpose of this discussion, the formula for H becomes

$$H = H_1 = \frac{3.56 \times 10^5 T_b}{W(T_r + T_b)} X \quad \text{when } c/g \leq 10 \quad (19)$$

and

$$H = H_2 = \frac{10 T_r T_b}{(T_r + T_b)} X \quad \text{when } c/g > 10 \quad (20)$$

in which X has the value,

$$X = (1 - e^{-0.693t(T_r + T_b)/T_r T_b}) \quad (21)$$

In order to indicate the variation of H with T_r and T_b , the equations for H_1 and H_2 were plotted in Fig. 2 for various values of T_b and W and for an exposure period $t = 50y$, the occupational exposure period of the standard man. For a fixed

FIG. 2 VALUES OF RELATIVE HAZARD H AS A FUNCTION OF RADIOACTIVE HALF LIFE T_r FOR AN OCCUPATIONAL EXPOSURE PERIOD OF 50 YEARS AND FOR VARIOUS BIOLOGICAL HALF LIVES T_b AND ATOMIC WEIGHTS W

value of T_b , the relative hazard is plotted as a function T_r ; the curve continues to the cut-off value beyond which H decreases along the straight line. This cut-off value differs for different values of the atomic weight W . Table III summarizes some of the observations from Fig. 2. Here it is to be observed that for low values of T_b the maximum value of H increases rapidly with increasing values of T_b but for large values of T_b , it increases slowly with T_b and that H (max) is an insensitive function of W , i. e., H (max) decreases slowly with increasing W . The relative hazard H is always increased by an increase in T_b . The value of T_r at which H is a maximum is independent of T_b but it decreases linearly with increasing W . Some of these changes seem to be in accord with what one would expect from an equation that is to indicate the relative hazard of a radionuclide. Thus, when T_b is shorter than the life span of man, H increases rapidly with T_b ; but when T_b is much greater than the life span of man, there is little further increase of H with an increase of T_b . In other words, one would expect a large increase in the hazard if T_b were increased from one hour to one day to one year but would expect little increase in the hazard if T_b were increased from 1,000 years to 10,000 years. Also, the relative hazard H increases with increasing values of T_r when $c/g > 10$ and this rate of increase with T_r approaches linearity when both c/g and T_b are large (i. e., c/g and $T_b \rightarrow \infty$). The relative hazard H reaches a maximum at the values of W and T_r corresponding to $c/g = 10$. For values of $c/g < 10$ and for a fixed value of W , the decrease in H is inversely proportional to T_r . Thus, transuranic radionuclides with atomic weights from 238 to 256 are most hazardous if their radioactive half lives are above 150 years or approximately twice the average life span of man and fission products having an atomic weight of about 100 would be most hazardous if their radioactive half lives were about five times the average life span of man.

An inspection of the 12 highest values of H for radionuclides obtained by means of equation 16 (see Table VI) reveals that 10 of these 12 are transuranic elements and of these 10 there are six with values of T_r that are within an order of magnitude of 150y. All 12 of these radionuclides with highest values of H are "bone-seeking" radionuclides for which $n = 5$ and nine of these decay primarily by α -emission for

TABLE III

SUMMARY OF MAXIMUM VALUES OF H AND CORRESPONDING VALUES OF T_r (YEARS)
FOR VARIOUS VALUES OF T_b (YEARS) AND W AS PLOTTED IN FIG. 2

$T_b(y)$	Values of H (max) for W=240	Corresponding values of T_r for H (max) and for W=240	Values of H (max) for W=100	Corresponding Values of T_r for H (max) and for W=100	Values of H (max) for W=10	Corresponding Values of T_r for H (max) and for W=10	Values of H (max) for W=1	Corresponding Values of T_r for H (max) and for W=1
1	10	148	10	356	10	3560	10	35,600
50	230	148	240	356	250	3560	250	35,600
∞	310	148	330	356	340	3560	350	35,600

which (RBE) = 10. All 12 of these radionuclides with highest values of H are in the actinide group of elements for which a value of $T_b = 200$ years is assigned. It will be noted also that most of the fission products have much shorter half lives and smaller values of H than the transuranic elements and, in general, the greater the half lives (i. e., both T_r and T_b) of the fission product, the greater the value of H.

Equation 15b can be re-arranged in the forms

$$(MPC)_c = \frac{2.92 \times 10^{-11} \phi (c/g)}{H} \quad (22)$$

and

$$(MPC)_g = \frac{2.92 \times 10^{-11} \phi (c/g)}{c/g H} \quad (23)$$

in which $(MPC)_c$ and $(MPC)_g$ are the maximum permissible concentrations in the air in $\mu c/cc$ and $\mu g/cc$, respectively, for occupational exposure 40 hours per week. Values of $(MPC)_c$ and $(MPC)_g$ from equations 22 and 23 for $H = 1$, $H = 0.1$ and $H = 5 \times 10^{-4}$ are listed in Table IV and plotted in Fig. 3. It is to be noted that in each case plots of $(MPC)_c$ and $(MPC)_g$ for a constant value of H form rectangles in which the base is 1/10 of the height. It is to be observed also that radionuclides such as Am^{243} , Pu^{239} and Sr^{90} , as well as Ra^{226} , fall approximately upon a line which is the locus of points for which $H = 1$ or for which the hazard is unity. Radionuclides falling within the rectangle for which $H = 1$ have a relative hazard greater than 1; radionuclides falling within the rectangle for which $H = 0.1$ have a relative hazard greater than 0.1 and radionuclides falling between rectangles for which $H = 0.1$ and 5×10^{-4} have relative hazards within this range, etc. Thus, equations 22 and 23 provide rectangles such as plotted in Fig. 3 to furnish a convenient means of segregating the radionuclides into various relative hazard groups.

Table IV indicates also for illustration the variation with specific activity ($\mu c/\mu g$) of 1) the $\mu g/\mu c$ of the radionuclide, 2) the factor $\phi (c/g)$, 3) the dilution factor, μg of dust per μg of radionuclide, 4) the average specific activity of the

TABLE IV

ILLUSTRATIVE EXAMPLES INDICATING THE RELATIONSHIP BETWEEN THE
SPECIFIC ACTIVITY OF THE RADIONUCLIDE, THE SPECIFIC ACTIVITY
OF THE DUST AND VALUES OF $(MPC)_c$, $(MPC)_g$ AND H

Specific Activity of Radionuclide (μc/μg)	Mass per unit of activity of radionuclide (μg/μc)	ϕ(c/g)	Dilution factor (μg dust per μg of radionuclide)*	Average specific activity of dust in work area (μc/μg)*	Average mass per unit of activity of dust in work area (μg/μc)*	Values of (MPC) _c and (MPC) _g for the undiluted radionuclide if						Values of H Corresponding to a constant value of (MPC) _c = 2.9 x 10 ⁻¹⁰
						H = 1		H = 0.1		H = 5 x 10 ⁻⁴		
						(MPC) _c (μc/cc)	(MPC) _g (μg/cc)	(MPC) _c (μc/cc)	(MPC) _g (μg/cc)	(MPC) _c (μc/cc)	(MPC) _g (μg/cc)	
1000	0.001	10	3.4x10 ⁸	3x10 ⁻⁶	3.4x10 ⁵	3x10 ⁻¹⁰	3x10 ⁻¹³	3x10 ⁻⁹	3x10 ⁻¹²	6x10 ⁻⁷	6x10 ⁻¹⁰	1
100	0.01	10	3.4x10 ⁷	3x10 ⁻⁶	3.4x10 ⁵	3x10 ⁻¹⁰	3x10 ⁻¹²	3x10 ⁻⁹	3x10 ⁻¹¹	6x10 ⁻⁷	6x10 ⁻⁹	1
10	0.1	10	3.4x10 ⁶	3x10 ⁻⁶	3.4x10 ⁵	3x10 ⁻¹⁰	3x10 ⁻¹¹	3x10 ⁻⁹	3x10 ⁻¹⁰	6x10 ⁻⁷	6x10 ⁻⁸	1
1	1	1	3.4x10 ⁶	3x10 ⁻⁷	3.4x10 ⁶	3x10 ⁻¹¹	3x10 ⁻¹¹	3x10 ⁻¹⁰	3x10 ⁻¹⁰	6x10 ⁻⁸	6x10 ⁻⁸	0.1
0.1	10	0.1	3.4x10 ⁶	3x10 ⁻⁸	3.4x10 ⁷	3x10 ⁻¹²	3x10 ⁻¹¹	3x10 ⁻¹¹	3x10 ⁻¹⁰	6x10 ⁻⁹	6x10 ⁻⁸	10 ⁻²
0.01	100	0.01	3.4x10 ⁶	3x10 ⁻⁹	3.4x10 ⁸	3x10 ⁻¹³	3x10 ⁻¹¹	3x10 ⁻¹²	3x10 ⁻¹⁰	6x10 ⁻¹⁰	6x10 ⁻⁸	10 ⁻³
0.001	1000	0.001	3.4x10 ⁶	3x10 ⁻¹⁰	3.4x10 ⁹	3x10 ⁻¹⁴	3x10 ⁻¹¹	3x10 ⁻¹³	3x10 ⁻¹⁰	6x10 ⁻¹¹	6x10 ⁻⁸	10 ⁻⁴

*The constant dilution factors $(b + 1)(d + 1)$ were set equal to 3.43×10^6 by normalizing the hazard H to 1 for Ra^{226} and assuming a constant dust loading of $10^{-4} \mu\text{g}/\text{cc}$.

dust, $\mu\text{c}/\mu\text{g}$ of dust, 5) the average mass per unit activity of dust, μg dust per μc and 6) values of relative hazard H corresponding to a $(\text{MPC})_c = 2.92 \times 10^{-10} \mu\text{c}/\text{cc}$.

A close inspection of Fig. 3 indicates that the $(\text{MPC})_c$ values for most of the uranium radioisotopes are very nearly the same. This suggests that it might be of interest to consider the resulting hazard for various mixtures of the uranium isotopes in order to illustrate further the influence of specific activity ($\mu\text{c}/\mu\text{g}$) or T_r on the relative hazard H . Table V summarizes values of mass per unit activity $\mu\text{g}/\mu\text{c}$ of isotopic mixtures of U^{235} and U^{230} , mass per unit activity $\mu\text{g}/\mu\text{c}$ of the airborne dust, $(\text{MPC})_c$, $(\text{MPC})_g$ and H for the various mixtures. These values of $(\text{MPC})_c$ and $(\text{MPC})_g$ are plotted in Fig. 3, forming a line -- one that is almost horizontal -- connecting the points for U^{235} and U^{230} . It is to be noted that as U^{235} is diluted with U^{230} , the mass of airborne dust per unit activity decreases linearly with the increase in specific activity of the isotopic mixture and the relative hazard H increases almost linearly with the specific activity of the isotopic mixture until the specific activity of the isotopic mixture reaches $10 \mu\text{c}/\mu\text{g}$. Thereafter, the average mass of airborne dust per unit activity remains constant at $3.4 \times 10^5 \mu\text{g}/\mu\text{c}$ and the relative hazard H remains constant at the value of 2.56.

As stated above, many writers have listed the radionuclides into relative hazard groups, but it is the opinion of these writers that the method suggested by Duhamel and Lavie³ in 1959 is second in choice only to the method suggested by Morgan, Snyder and Ford¹ in 1956 and as further extended here. Thus, the purpose of the authors of this paper has been to establish a more detailed explanation and perhaps a better theoretical basis for the method suggested in 1956 and to compare the results of this method with those suggested by other writers. Whereas this method, as noted in Fig. 3, yields a series of rectangles with the base $1/10$ of the height, the method of Duhamel and Lavie yields a series of triangles with the base 10^{-4} of the height. The diagonals of these triangles are plotted in Fig. 3 by normalizing equation 4 so that $H = 1$ for Ra^{226} . It will be noted that the line $(\text{DL})_1$, as well as the line marked $H = 1$, pass through the point for Ra^{226} and, by the method of Duhamel and Lavie, radionuclides falling below the diagonal line marked $(\text{DL})_1$

FIG. 1 RELATIVE HAZARD GROUPING OF THE RADIONUCLIDES AS SUGGESTED BY SEVERAL AUTHORS. THE RECTANGLES MARKED $H=1$, $H=0.1$ AND $H=5 \times 10^{-4}$ ENCLOSE RADIONUCLIDES WITH RELATIVE HAZARDS GREATER THAN 1, GREATER THAN 0.1 AND GREATER THAN 5×10^{-4} RESPECTIVELY AS DEFINED BY THE METHOD OF THIS PAPER. THE TRIANGLES MARKED $(DL)_1$, $(DL)_2$ AND $(DL)_3$ ENCLOSE RADIONUCLIDES OF DECREASING RELATIVE HAZARDS AS DEFINED BY THE METHOD OF DUMAS AND LANGE. THE IRREGULAR LINES MARKED $(IAEA)_1$ AND $(IAEA)_2$ ENCLOSE RADIONUCLIDES OF DECREASING RELATIVE HAZARDS AS DEFINED IN IAEA¹ REPORTS AND THE LINES MARKED $(USSR)_1$ AND $(USSR)_2$ ENCLOSE RADIONUCLIDES OF DECREASING HAZARDS AS DEFINED IN USSR² REPORTS.

TABLE V

RELATIVE HAZARD, H, FOR A MIXTURE OF U^{230} AND U^{235}

Radio-activity in mixture due to U^{235} (%)	Radio-activity in mixture due to U^{230} (%)	Mass per unit activity of isotope mixture ($\mu\text{g}/\mu\text{c}$)	Specific activity of isotope mixture ($\mu\text{c}/\mu\text{g}$)	Average mass per unit activity of dust in work area* ($\mu\text{g}/\mu\text{c}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	(MPC) _g ($\mu\text{g}/\text{cc}$)	H
100	0	4.68×10^5	2.14×10^{-6}	1.6×10^{12}	1.28×10^{-10}	5.99×10^{-5}	4.88×10^{-7}
10	90	4.68×10^4	2.14×10^{-5}	1.6×10^{11}	1.15×10^{-10}	5.38×10^{-6}	5.42×10^{-6}
10^{-1}	99.9	4.68×10^2	2.14×10^{-3}	1.6×10^9	1.14×10^{-10}	5.32×10^{-8}	5.48×10^{-4}
10^{-3}	99.999	4.68	2.14×10^{-1}	1.6×10^7	1.14×10^{-10}	5.32×10^{-10}	5.48×10^{-2}
2.14×10^{-5}	99.99+	0.1	10	3.4×10^5	1.14×10^{-10}	1.14×10^{-11}	2.56
10^{-7}	99.99+	5.05×10^{-4}	1.98×10^3	3.4×10^5	1.14×10^{-10}	5.76×10^{-14}	2.56
0	100	3.66×10^{-5}	2.73×10^4	3.4×10^5	1.14×10^{-10}	4.17×10^{-15}	2.56

*Assuming a constant dilution factor $(b + 1)(d + 1) = 3.43 \times 10^6$ or a total dilution factor of $3.43 \times 10^6 \times (c/g)/\phi(c/g)$

have a relative hazard >1 . Radionuclides falling below the diagonal line marked $(DL)_2$ have a relative hazard >0.293 and were placed in the very hazardous group. Radionuclides falling between the diagonal lines $(DL)_2$ and $(DL)_3$ have a relative hazard between 0.293 and 2.93×10^{-3} and were placed in the intermediately hazardous group, and radionuclides falling above the line $(DL)_3$ have a relative hazard $<2.92 \times 10^{-3}$ and were placed in the less hazardous group. By the method of the present paper (by Morgan, Snyder and Ford), radionuclides falling within the rectangle marked $H = 0.1$ have a hazard >0.1 and were placed in the very hazardous group; those falling between the rectangles marked $H = 0.1$ and $H = 5 \times 10^{-4}$ have a relative hazard between 0.1 and 5×10^{-4} and were placed in the intermediately hazardous group and radionuclides falling above the rectangle marked $H = 5 \times 10^{-4}$ have a relative hazard $<5 \times 10^{-4}$ and were placed in the less hazardous group. How many groups of radionuclides should be established and what boundaries of H should be selected for their demarcation depends upon the use that is to be made of these groups. The method suggested in this paper for obtaining H for the radionuclides and for various chemical forms and isotopic dilutions of the radionuclides permits any convenient grouping of the radionuclides in terms of the relative hazard. Some of the uses of these relative hazard groups are 1) to aid in the adoption of protective measures, 2) to determine laboratory facilities and equipment requirements, 3) to indicate the essential shipping regulations, and 4) to aid in determining what quantities of a radionuclide can be considered as "exempt" from special regulations, etc.

A number of other groupings of radionuclides have been suggested but, for the most part, these have been suggested without offering any substantial theoretical basis and, in many cases, the groupings do not conform with laboratory experience regarding the relative hazard of these radionuclides. In Fig. 3, boundary lines are drawn to enclose radionuclides in the various hazard groups and, in some cases, it is noted that the lines are very irregular. For example, the radionuclides falling below the line marked $(IAEA)_1$ are listed by the International Atomic Energy Agency⁷ as belonging in their Group I which is referred to as having "very high radiotoxicity."

Radionuclides falling between the lines marked $(IAEA)_1$ and $(IAEA)_2$ are listed by IAEA as belonging within their Group II which is referred to as radionuclides of "high radiotoxicity." Those falling above the line marked $(IAEA)_2$ are listed by IAEA as belonging within their Group III which is referred to as radionuclides of moderate or low radiotoxicity. Likewise, radionuclides falling below the line marked $(USSR)_1$ are listed in the report of the Ministry of Health of the USSR⁸ as belonging in the Group A of radionuclides of "especially high radiotoxicity" and those falling between the lines marked $(USSR)_1$ and $(USSR)_2$ are listed as belonging in Group B of radionuclides of "high radiotoxicity," etc. No effort has been made in constructing the boundary lines in Fig. 3 to include the groupings of radionuclides as suggested by all the various individuals and organizations but rather to give typical examples, indicating the wide variations between the methods suggested and to show some of the irregularities of other methods in comparison with the orderly arrangement provided by the method of this paper.

It should be pointed out that Fig. 3 and Table VI include a number of transuranic radionuclides which have not been published in any previous grouping of radionuclides. These values of $(MPC)_c$ have been calculated using the methods given in ICRP⁴ Publication No. 2, and they have now been adopted and will be published by ICRP⁹ as officially recommended $(MPC)_c$ values. Table VI summarizes values of critical body organ, specific activity, $(MPC)_c$ and H for the various radionuclides listed in ICRP Publication No. 2, as well as for the new group of transuranic elements in ICRP Publication No. 6.

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TABLE VI

SUMMARY OF VALUES OF SPECIFIC ACTIVITY, $(MPC)_c$ AND RELATIVE HAZARD, H

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	$(MPC)_c$ ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	$(MPC)_c$ ($\mu\text{c}/\text{cc}$)	Relative Hazard H
1H^3	BT(S)	9.67×10^3	5.26×10^{-6}	5.56×10^{-5}	20Ca^{45}	B(S)	1.77×10^4	3.21×10^{-8}	9.09×10^{-3}
4Be^7	L(I)	3.48×10^5	1.20×10^{-6}	2.44×10^{-4}	20Ca^{47}	LLI(I)	5.67×10^5	1.69×10^{-7}	1.72×10^{-3}
6C^{14}	Fat(S)	4.66	3.50×10^{-6}	3.88×10^{-5}	21Sc^{46}	L(I)	3.34×10^4	2.22×10^{-8}	1.32×10^{-2}
9F^{18}	ULI(I)	9.32×10^7	2.57×10^{-6}	1.14×10^{-4}	21Sc^{47}	LLI(I)	8.11×10^5	4.67×10^{-7}	6.25×10^{-4}
11Na^{22}	L(I)	6.24×10^3	8.91×10^{-9}	3.28×10^{-2}	21Sc^{48}	LLI(I)	1.49×10^6	1.40×10^{-7}	2.08×10^{-3}
11Na^{24}	LLI(I)	8.64×10^6	1.43×10^{-7}	2.04×10^{-3}	23V^{48}	L(I)	1.69×10^5	5.55×10^{-8}	5.26×10^{-3}
14Si^{31}	ULI(I)	3.83×10^7	9.93×10^{-7}	2.94×10^{-4}	24Cr^{51}	L(I)	9.19×10^4	2.25×10^{-6}	1.30×10^{-4}
15P^{32}	B(S)	2.85×10^5	7.01×10^{-8}	4.17×10^{-3}	25Mn^{52}	L(I)	4.52×10^5	1.40×10^{-7}	2.08×10^{-3}
16S^{35}	L(I)	4.28×10^4	2.51×10^{-7}	1.16×10^{-3}	25Mn^{54}	L(I)	8.06×10^3	3.50×10^{-8}	8.33×10^{-3}
17Cl^{36}	L(I)	3.02×10^{-2}	2.28×10^{-8}	3.87×10^{-5}	25Mn^{56}	LLI(I)	2.12×10^7	5.26×10^{-7}	5.56×10^{-4}
17Cl^{38}	ST(I)	1.32×10^8	2.04×10^{-6}	1.43×10^{-4}	26Fe^{55}	SP(S)	2.16×10^3	8.76×10^{-7}	3.33×10^{-4}
18A^{37}	SK(Su)	1.04×10^5	6.37×10^{-3}	4.59×10^{-8}	26Fe^{59}	L(I)	4.91×10^4	5.26×10^{-8}	5.56×10^{-3}
18A^{41}	TB(Su)	4.18×10^7	1.58×10^{-6}	1.85×10^{-4}	27Co^{57}	L(I)	8.47×10^3	1.61×10^{-7}	1.82×10^{-3}
40K^{42}	LLI(I)	5.99×10^6	1.08×10^{-7}	2.70×10^{-3}	27Co^{58}	L(I)	5.93×10^6	8.76×10^{-6}	3.33×10^{-5}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{58}\text{Co}^{27}$	L(I)	3.12×10^4	5.40×10^{-8}	5.41×10^{-3}	$^{77}\text{As}^{33}$	LLI(I)	1.04×10^6	4.09×10^{-7}	7.14×10^{-4}
$^{60}\text{Co}^{27}$	L(I)	1.14×10^3	8.76×10^{-9}	3.33×10^{-2}	$^{75}\text{Se}^{34}$	L(I)	1.37×10^4	1.23×10^{-7}	2.38×10^{-3}
$^{59}\text{Ni}^{28}$	B(S)	7.63×10^{-2}	4.67×10^{-7}	4.77×10^{-6}	$^{82}\text{Br}^{35}$	LLI(I)	1.06×10^6	1.90×10^{-7}	1.54×10^{-3}
$^{63}\text{Ni}^{28}$	B(S)	7.13×10^1	6.42×10^{-8}	4.55×10^{-3}	$^{85\text{m}}\text{Kr}^{36}$	TB(Su)	8.53×10^6	6.13×10^{-6}	4.76×10^{-5}
$^{65}\text{Ni}^{28}$	ULI(I)	1.83×10^7	5.26×10^{-7}	5.56×10^{-4}	$^{85}\text{Kr}^{36}$	TB(Su)	3.93×10^2	1.18×10^{-5}	2.47×10^{-5}
$^{64}\text{Cu}^{29}$	LLI(I)	3.85×10^6	1.05×10^{-6}	2.78×10^{-4}	$^{87}\text{Kr}^{36}$	TB(Su)	2.78×10^7	1.01×10^{-6}	2.90×10^{-4}
$^{65}\text{Zn}^{30}$	L(I)	8.21×10^3	5.84×10^{-8}	5.00×10^{-3}	$^{86}\text{Rb}^{37}$	L(I)	8.16×10^4	6.72×10^{-8}	4.35×10^{-3}
$^{69\text{m}}\text{Zn}^{30}$	LLI(I)	3.26×10^6	3.21×10^{-7}	9.09×10^{-4}	$^{87}\text{Rb}^{37}$	L(I)	8.31×10^{-8}	6.54×10^{-8}	3.71×10^{-11}
$^{69}\text{Zn}^{30}$	PR(S)	5.26×10^7	7.01×10^{-6}	4.17×10^{-5}	$^{85\text{m}}\text{Sr}^{38}$	SI(I)	3.13×10^7	3.47×10^{-5}	8.40×10^{-6}
$^{72}\text{Ga}^{31}$	LLI(I)	3.07×10^6	1.90×10^{-7}	1.54×10^{-3}	$^{85}\text{Sr}^{38}$	L(I)	2.36×10^4	1.05×10^{-7}	2.78×10^{-3}
$^{71}\text{Ge}^{32}$	L(I)	1.53×10^5	6.42×10^{-6}	4.55×10^{-5}	$^{89}\text{Sr}^{38}$	B(S)	2.91×10^4	2.77×10^{-8}	1.05×10^{-2}
$^{73}\text{As}^{33}$	L(I)	2.35×10^4	3.80×10^{-7}	7.69×10^{-4}	$^{90}\text{Sr}^{38}$	B(S)	1.45×10^2	2.89×10^{-10}	1.01
$^{74}\text{As}^{33}$	L(I)	1.00×10^5	1.26×10^{-7}	2.33×10^{-3}	$^{91}\text{Sr}^{38}$	LLI(I)	3.59×10^6	2.51×10^{-7}	1.16×10^{-3}
$^{76}\text{As}^{33}$	LLI(I)	1.55×10^6	9.93×10^{-8}	2.94×10^{-3}	$^{92}\text{Sr}^{38}$	ULI(I)	1.29×10^7	2.92×10^{-7}	1.00×10^{-3}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
^{90}Y	LLI(I)	5.41×10^5	1.02×10^{-7}	2.86×10^{-3}	$^{97\text{m}}\text{Tc}$	L(I)	1.46×10^1	1.52×10^{-7}	1.92×10^{-3}
$^{91\text{m}}\text{Y}$	SI(I)	4.09×10^7	1.72×10^{-5}	1.69×10^{-5}	^{97}Tc	L(I)	3.64×10^{-1}	2.92×10^{-7}	3.64×10^{-5}
^{91}Y	L(I)	2.47×10^4	3.21×10^{-8}	9.09×10^{-3}	$^{99\text{m}}\text{Tc}$	ULI(I)	5.26×10^6	1.40×10^{-5}	2.08×10^{-5}
^{92}Y	ULI(I)	9.46×10^6	2.92×10^{-7}	1.00×10^{-3}	^{99}Tc	L(I)	1.80×10^{-2}	6.13×10^{-8}	8.60×10^{-6}
^{93}Y	LLI(I)	3.34×10^6	1.37×10^{-7}	2.13×10^{-3}	^{97}Ru	LLI(I)	4.80×10^5	1.78×10^{-6}	1.64×10^{-4}
^{93}Zr	B(S)	3.51×10^{-3}	1.11×10^{-7}	9.23×10^{-7}	^{103}Ru	L(I)	3.09×10^4	8.47×10^{-8}	3.45×10^{-3}
^{95}Zr	L(I)	2.17×10^4	3.21×10^{-8}	9.09×10^{-3}	^{105}Ru	ULI(I)	6.52×10^6	5.26×10^{-7}	5.56×10^{-4}
^{97}Zr	LLI(I)	1.89×10^6	9.05×10^{-8}	3.23×10^{-3}	^{106}Ru	L(I)	3.37×10^3	5.55×10^{-9}	5.26×10^{-2}
$^{93\text{m}}\text{Nb}$	B(S)	3.79×10^2	1.23×10^{-7}	2.38×10^{-3}	$^{103\text{m}}\text{Rh}$	SI(I)	3.34×10^7	6.13×10^{-5}	4.76×10^{-6}
^{95}Nb	L(I)	3.92×10^4	9.93×10^{-8}	2.94×10^{-3}	^{105}Rh	LLI(I)	8.16×10^5	5.26×10^{-7}	5.56×10^{-4}
^{97}Nb	ULI(I)	2.64×10^7	4.67×10^{-6}	6.25×10^{-5}	^{103}Pd	L(I)	7.46×10^4	7.48×10^{-7}	3.91×10^{-4}
^{99}Mo	LLI(I)	4.73×10^5	2.01×10^{-7}	1.45×10^{-3}	^{109}Pd	LLI(I)	2.10×10^6	3.50×10^{-7}	8.33×10^{-4}
$^{96\text{m}}\text{Tc}$	L(I)	3.77×10^7	2.92×10^{-5}	10×10^{-6}	^{105}Ag	L(I)	3.11×10^4	8.18×10^{-8}	3.57×10^{-3}
^{96}Tc	LLI(I)	3.16×10^5	2.42×10^{-7}	1.20×10^{-3}	$^{110\text{m}}\text{Ag}$	L(I)	4.39×10^3	1.02×10^{-8}	2.86×10^{-2}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$_{47}\text{Ag}^{111}$	LLI(I)	1.57×10^5	2.22×10^{-7}	1.32×10^{-3}	$_{52}\text{Te}^{127\text{m}}$	L(I)	9.81×10^3	4.09×10^{-8}	7.14×10^{-3}
$_{48}\text{Cd}^{109}$	LIV(S)	2.52×10^3	5.26×10^{-8}	5.56×10^{-3}	$_{52}\text{Te}^{127}$	LLI(I)	2.64×10^6	8.53×10^{-7}	3.42×10^{-4}
$_{48}\text{Cd}^{115\text{m}}$	LIV(S)	2.64×10^4	3.50×10^{-8}	8.33×10^{-3}	$_{52}\text{Te}^{129\text{m}}$	L(I)	3.06×10^4	3.21×10^{-8}	9.09×10^{-3}
$_{48}\text{Cd}^{115}$	LLI(I)	5.16×10^5	1.84×10^{-7}	1.59×10^{-3}	$_{52}\text{Te}^{129}$	ULI(I)	1.98×10^7	4.09×10^{-6}	7.14×10^{-5}
$_{49}\text{In}^{113\text{m}}$	ULI(I)	1.58×10^7	6.72×10^{-6}	4.35×10^{-5}	$_{52}\text{Te}^{131\text{m}}$	LLI(I)	7.96×10^5	1.90×10^{-7}	1.54×10^{-3}
$_{49}\text{In}^{114\text{m}}$	L(I)	2.33×10^4	2.16×10^{-8}	1.35×10^{-2}	$_{52}\text{Te}^{132}$	LLI(I)	3.09×10^5	1.05×10^{-7}	2.78×10^{-3}
$_{49}\text{In}^{115\text{m}}$	ULI(I)	5.96×10^6	1.87×10^{-6}	1.56×10^{-4}	$_{53}\text{I}^{126}$	TH(S)	7.77×10^4	7.88×10^{-9}	3.70×10^{-2}
$_{49}\text{In}^{115}$	L(I)	5.16×10^{-12}	3.47×10^{-8}	4.33×10^{-15}	$_{53}\text{I}^{129}$	TH(S)	1.61×10^{-4}	1.61×10^{-9}	2.92×10^{-6}
$_{50}\text{Sn}^{113}$	L(I)	1.03×10^4	5.26×10^{-8}	5.56×10^{-3}	$_{53}\text{I}^{131}$	TH(S)	1.24×10^5	8.53×10^{-9}	3.42×10^{-2}
$_{50}\text{Sn}^{125}$	L(I)	1.10×10^5	8.47×10^{-8}	3.45×10^{-3}	$_{53}\text{I}^{132}$	TH(S)	1.02×10^7	2.34×10^{-7}	1.25×10^{-3}
$_{51}\text{Sb}^{122}$	LLI(I)	3.82×10^5	1.46×10^{-7}	2.00×10^{-3}	$_{53}\text{I}^{133}$	TH(S)	1.12×10^6	3.21×10^{-8}	9.09×10^{-3}
$_{51}\text{Sb}^{124}$	L(I)	1.75×10^4	1.93×10^{-8}	1.52×10^{-2}	$_{53}\text{I}^{134}$	TH(S)	2.71×10^7	4.96×10^{-7}	5.88×10^{-4}
$_{51}\text{Sb}^{125}$	L(I)	1.19×10^3	2.66×10^{-8}	1.10×10^{-2}	$_{53}\text{I}^{135}$	TH(S)	3.45×10^6	1.05×10^{-7}	2.78×10^{-3}
$_{52}\text{Te}^{125\text{m}}$	L(I)	1.80×10^4	1.28×10^{-7}	2.27×10^{-3}	$_{54}\text{Xe}^{131\text{m}}$	TB(Su)	8.31×10^4	1.75×10^{-5}	1.67×10^{-5}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{133}_{54}\text{Xe}$	TB(Su)	1.86×10^5	1.49×10^{-5}	1.96×10^{-5}	$^{142}_{59}\text{Pr}$	LLI(I)	1.14×10^6	1.58×10^{-7}	1.85×10^{-3}
$^{135}_{54}\text{Xe}$	TB(Su)	2.54×10^6	4.38×10^{-6}	6.67×10^{-5}	$^{143}_{59}\text{Pr}$	L(I)	6.66×10^4	1.78×10^{-7}	1.64×10^{-3}
$^{131}_{55}\text{Cs}$	L(I)	9.96×10^4	3.21×10^{-6}	9.09×10^{-5}	$^{144}_{60}\text{Nd}$	B(S)	1.24×10^{-12}	8.18×10^{-11}	4.44×10^{-13}
$^{134\text{m}}_{55}\text{Cs}$	ULI(I)	7.50×10^6	5.84×10^{-6}	5.00×10^{-5}	$^{147}_{60}\text{Nd}$	L(I)	7.86×10^4	2.28×10^{-7}	1.28×10^{-3}
$^{134}_{55}\text{Cs}$	L(I)	1.15×10^3	1.17×10^{-8}	2.50×10^{-2}	$^{149}_{60}\text{Nd}$	ULI(I)	1.05×10^7	1.46×10^{-6}	2.00×10^{-4}
$^{135}_{55}\text{Cs}$	L(I)	8.76×10^{-4}	9.05×10^{-8}	2.83×10^{-7}	$^{147}_{61}\text{Pm}$	B(S)	9.67×10^2	6.42×10^{-8}	4.55×10^{-3}
$^{136}_{55}\text{Cs}$	L(I)	7.37×10^4	1.69×10^{-7}	1.72×10^{-3}	$^{149}_{61}\text{Pm}$	LLI(I)	3.98×10^5	2.25×10^{-7}	1.30×10^{-3}
$^{137}_{55}\text{Cs}$	L(I)	8.64×10^1	1.46×10^{-8}	2.00×10^{-2}	$^{147}_{62}\text{Sm}$	B(S)	1.85×10^{-8}	7.01×10^{-11}	7.70×10^{-9}
$^{131}_{56}\text{Ba}$	L(I)	8.59×10^4	3.50×10^{-7}	8.33×10^{-4}	$^{151}_{62}\text{Sm}$	B(S)	2.33×10^1	6.42×10^{-8}	4.55×10^{-3}
$^{140}_{56}\text{Ba}$	L(I)	7.29×10^4	4.38×10^{-8}	6.67×10^{-3}	$^{153}_{62}\text{Sm}$	LLI(I)	4.35×10^5	4.09×10^{-7}	7.14×10^{-4}
$^{140}_{57}\text{La}$	LLI(I)	5.55×10^5	1.23×10^{-7}	2.38×10^{-3}	$^{152}_{63}\text{Eu}$	LLI(I)	2.26×10^6	3.21×10^{-7}	9.09×10^{-4}
$^{141}_{58}\text{Ce}$	L(I)	2.89×10^4	1.58×10^{-7}	1.85×10^{-3}	$^{152}_{63}\text{Eu}$	KI(S)	1.83×10^2	1.23×10^{-8}	2.38×10^{-2}
$^{143}_{58}\text{Ce}$	LLI(I)	6.87×10^5	2.07×10^{-7}	1.41×10^{-3}	$^{154}_{63}\text{Eu}$	KI(S)	1.46×10^2	3.80×10^{-9}	7.69×10^{-2}
$^{144}_{58}\text{Ce}$	L(I)	3.12×10^3	6.42×10^{-9}	4.55×10^{-2}	$^{155}_{63}\text{Eu}$	L(I)	1.36×10^3	7.30×10^{-8}	4.00×10^{-3}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{153}_{64}\text{Gd}$	L(I)	3.61×10^3	9.05×10^{-8}	3.23×10^{-3}	$^{181}_{74}\text{W}$	L(I)	5.16×10^3	1.26×10^{-7}	2.33×10^{-3}
$^{159}_{64}\text{Gd}$	LLI(I)	1.10×10^6	4.09×10^{-7}	7.14×10^{-4}	$^{185}_{74}\text{W}$	L(I)	9.53×10^3	1.11×10^{-7}	2.63×10^{-3}
$^{160}_{65}\text{Tb}$	L(I)	1.12×10^4	3.21×10^{-8}	9.09×10^{-3}	$^{187}_{74}\text{W}$	LLI(I)	6.98×10^5	3.21×10^{-7}	9.09×10^{-4}
$^{165}_{66}\text{Dy}$	ULI(I)	8.16×10^6	2.07×10^{-6}	1.41×10^{-4}	$^{183}_{75}\text{Re}$	L(I)	9.74×10^3	1.58×10^{-7}	1.85×10^{-3}
$^{166}_{66}\text{Dy}$	LLI(I)	2.31×10^5	1.96×10^{-7}	1.49×10^{-3}	$^{186}_{75}\text{Re}$	LLI(I)	1.85×10^5	2.39×10^{-7}	1.22×10^{-3}
$^{166}_{67}\text{Ho}$	LLI(I)	7.13×10^5	1.61×10^{-7}	1.82×10^{-3}	$^{187}_{75}\text{Re}$	L(I)	3.87×10^{-8}	4.96×10^{-7}	2.28×10^{-12}
$^{169}_{68}\text{Er}$	L(I)	8.21×10^4	3.80×10^{-7}	7.69×10^{-4}	$^{188}_{75}\text{Re}$	LLI(I)	9.81×10^5	1.61×10^{-7}	1.82×10^{-3}
$^{171}_{68}\text{Er}$	ULI(I)	2.46×10^6	5.84×10^{-7}	5.00×10^{-4}	$^{185}_{76}\text{Os}$	L(I)	7.41×10^3	4.67×10^{-8}	6.25×10^{-3}
$^{170}_{69}\text{Tm}$	L(I)	6.04×10^3	3.45×10^{-8}	8.47×10^{-3}	$^{191\text{m}}_{76}\text{Os}$	L(I)	1.18×10^6	9.34×10^{-6}	3.12×10^{-5}
$^{171}_{69}\text{Tm}$	B(S)	1.10×10^3	1.11×10^{-7}	2.63×10^{-3}	$^{191}_{76}\text{Os}$	L(I)	4.26×10^4	4.09×10^{-7}	7.14×10^{-4}
$^{175}_{70}\text{Yb}$	LLI(I)	1.82×10^5	5.84×10^{-7}	5.00×10^{-4}	$^{193}_{76}\text{Os}$	LLI(I)	5.16×10^5	2.74×10^{-7}	1.06×10^{-3}
$^{177}_{71}\text{Lu}$	LLI(I)	1.10×10^5	5.26×10^{-7}	5.56×10^{-4}	$^{190}_{77}\text{Ir}$	L(I)	5.72×10^4	4.09×10^{-7}	7.14×10^{-4}
$^{181}_{72}\text{Hf}$	SP(S)	1.57×10^4	3.80×10^{-8}	7.69×10^{-3}	$^{192}_{77}\text{Ir}$	L(I)	9.13×10^3	2.57×10^{-8}	1.14×10^{-2}
$^{182}_{73}\text{Ta}$	L(I)	6.40×10^3	2.19×10^{-8}	1.33×10^{-2}	$^{194}_{77}\text{Ir}$	LLI(I)	8.53×10^5	1.55×10^{-7}	1.89×10^{-3}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
^{191}Pt	LLI(I)	2.28×10^5	5.55×10^{-7}	5.26×10^{-4}	^{204}Ti	L(I)	5.83×10^2	2.63×10^{-8}	1.11×10^{-2}
$^{193\text{m}}\text{Pt}$	LLI(I)	1.93×10^5	5.26×10^{-6}	5.56×10^{-5}	^{203}Pb	LLI(I)	2.96×10^5	1.81×10^{-6}	1.61×10^{-4}
^{193}Pt	L(I)	3.76	3.21×10^{-7}	3.42×10^{-4}	^{210}Pb	KI(S)	8.76×10^1	1.26×10^{-10}	2.33
$^{197\text{m}}\text{Pt}$	ULI(I)	1.19×10^7	4.67×10^{-6}	6.25×10^{-5}	^{212}Pb	KI(S)	1.40×10^6	1.75×10^{-8}	1.67×10^{-2}
^{197}Pt	LLI(I)	8.82×10^5	5.55×10^{-7}	5.26×10^{-4}	^{206}Bi	L(I)	9.89×10^4	1.46×10^{-7}	2.00×10^{-3}
^{196}Au	L(I)	1.19×10^5	6.13×10^{-7}	4.76×10^{-4}	^{207}Bi	L(I)	2.17×10^2	1.37×10^{-8}	2.13×10^{-2}
^{198}Au	LLI(I)	2.44×10^5	2.37×10^{-7}	1.23×10^{-3}	^{210}Bi	L(I)	1.24×10^5	5.84×10^{-9}	5.00×10^{-2}
^{199}Au	LLI(I)	2.08×10^5	8.18×10^{-7}	3.57×10^{-4}	^{212}Bi	KI(S)	1.47×10^7	9.64×10^{-8}	3.03×10^{-3}
$^{197\text{m}}\text{Hg}$	KI(S)	6.62×10^5	7.30×10^{-7}	4.00×10^{-4}	^{210}Po	L(I)	4.48×10^3	2.01×10^{-10}	1.45
^{197}Hg	KI(S)	2.45×10^5	1.17×10^{-6}	2.50×10^{-4}	^{211}At	TH(S)	2.06×10^6	7.01×10^{-9}	4.17×10^{-2}
^{203}Hg	KI(S)	1.40×10^4	7.01×10^{-8}	4.17×10^{-3}	^{220}Rn	L(S)	9.89×10^8	2.92×10^{-7}	1.00×10^{-3}
^{200}Ti	LLI(I)	5.77×10^5	1.14×10^{-6}	2.56×10^{-4}	^{222}Rn	L(S)	1.54×10^5	2.92×10^{-8}	1.00×10^{-2}
^{201}Ti	LLI(I)	2.16×10^5	8.76×10^{-7}	3.33×10^{-4}	^{223}Ra	L(I)	5.00×10^4	2.39×10^{-10}	1.22
^{202}Ti	L(I)	5.39×10^4	2.39×10^{-7}	1.22×10^{-3}	^{224}Ra	L(I)	1.60×10^5	7.30×10^{-10}	4.00×10^{-1}

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{88}\text{Ra}^{226}$	B(S)	9.81×10^{-1}	2.86×10^{-11}	1.00	$^{92}\text{U}^{230}$	L(I)	2.73×10^4	1.14×10^{-10}	2.56
$^{88}\text{Ra}^{228}$	L(I)	2.39×10^2	3.80×10^{-11}	7.69	$^{92}\text{U}^{232}$	L(I)	2.08×10^1	2.77×10^{-11}	1.05×10^1
$^{89}\text{Ac}^{227}$	B(S)	7.17×10^1	2.34×10^{-12}	1.25×10^2	$^{92}\text{U}^{233}$	L(I)	9.53×10^{-3}	1.17×10^{-10}	2.38×10^{-3}
$^{89}\text{Ac}^{228}$	L(I)	2.20×10^6	1.69×10^{-8}	1.72×10^{-2}	$^{92}\text{U}^{234}$	L(I)	6.13×10^{-3}	1.20×10^{-10}	1.49×10^{-3}
$^{90}\text{Th}^{227}$	L(I)	3.12×10^4	1.81×10^{-10}	1.61	$^{92}\text{U}^{235}$	L(I)	2.14×10^{-6}	1.28×10^{-10}	4.85×10^{-7}
$^{90}\text{Th}^{228}$	L(I)	8.16×10^2	6.13×10^{-12}	4.76×10^1	$^{92}\text{U}^{236}$	L(I)	6.37×10^{-5}	1.26×10^{-10}	1.48×10^{-5}
$^{90}\text{Th}^{230}$	B(S)	1.96×10^{-2}	2.25×10^{-12}	2.54×10^{-1}	$^{92}\text{U}^{238}$	KI(S)	3.43×10^{-7}	7.30×10^{-11}	1.37×10^{-7}
$^{90}\text{Th}^{231}$	LLI(I)	5.28×10^5	1.20×10^{-6}	2.44×10^{-4}	$^{92}\text{U}^{240}$	LLI(I)	9.19×10^5	1.75×10^{-7}	1.67×10^{-3}
$^{90}\text{Th}^{232}$	B(S)	1.11×10^{-7}	1.93×10^{-12}	1.68×10^{-6}	$^{92}\text{U-nat}$	L(I)	3.30×10^{-7}	6.42×10^{-11}	1.50×10^{-7}
$^{90}\text{Th}^{234}$	L(I)	2.31×10^4	3.21×10^{-8}	9.09×10^{-3}	$^{93}\text{Np}^{237}$	B(S)	6.87×10^{-4}	4.09×10^{-12}	4.91×10^{-3}
$^{90}\text{Th-nat}$	B(S)	1.11×10^{-7}	1.61×10^{-12}	2.01×10^{-6}	$^{93}\text{Np}^{239}$	LLI(I)	2.34×10^5	6.54×10^{-7}	4.46×10^{-4}
$^{91}\text{Pa}^{230}$	L(I)	3.21×10^4	7.88×10^{-10}	3.70×10^{-1}	$^{94}\text{Pu}^{238}$	B(S)	1.66×10^1	1.93×10^{-12}	1.52×10^2
$^{91}\text{Pa}^{231}$	B(S)	4.35×10^{-2}	1.14×10^{-12}	1.12	$^{94}\text{Pu}^{239}$	B(S)	6.13×10^{-2}	1.72×10^{-12}	1.04
$^{91}\text{Pa}^{233}$	L(I)	2.05×10^4	1.75×10^{-7}	1.67×10^{-3}	$^{94}\text{Pu}^{240}$	B(S)	2.27×10^{-1}	1.72×10^{-12}	3.84

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{241}_{94}\text{Pu}$	B(S)	1.12×10^2	9.05×10^{-11}	3.23	$^{247}_{96}\text{Cm}$	B(S)	1.60×10^{-5}	4.64×10^{-12}	1.01×10^{-4}
$^{242}_{94}\text{Pu}$	B(S)	3.85×10^{-3}	1.81×10^{-12}	6.21×10^{-2}	$^{248}_{96}\text{Cm}$	B(S)	3.09×10^{-3}	5.69×10^{-13}	1.59×10^{-1}
$^{243}_{94}\text{Pu}$	ULI(I)	2.56×10^6	1.75×10^{-6}	1.67×10^{-4}	$^{249}_{96}\text{Cm}$	SI(I)	1.19×10^7	1.14×10^{-5}	2.56×10^{-5}
$^{244}_{94}\text{Pu}$	B(S)	1.91×10^{-5}	1.64×10^{-12}	3.41×10^{-4}	$^{249}_{97}\text{Bk}$	B(S)	1.81×10^3	9.34×10^{-10}	3.12×10^{-1}
$^{241}_{95}\text{Am}$	B(S)	3.18	5.84×10^{-12}	1.59×10^1	$^{250}_{97}\text{Bk}$	B(S)	4.02×10^6	1.46×10^{-7}	2.00×10^{-3}
$^{242\text{m}}_{95}\text{Am}$	B(S)	9.60	5.55×10^{-12}	5.05×10^1	$^{249}_{98}\text{Cf}$	B(S)	3.09	1.58×10^{-12}	5.71×10^1
$^{242}_{95}\text{Am}$	LIV(S)	8.06×10^5	3.88×10^{-8}	7.52×10^{-3}	$^{250}_{98}\text{Cf}$	B(S)	1.41×10^2	4.96×10^{-12}	5.88×10^1
$^{243}_{95}\text{Am}$	B(S)	1.85×10^{-1}	5.55×10^{-12}	9.74×10^{-1}	$^{251}_{98}\text{Cf}$	B(S)	1.79	1.66×10^{-12}	3.14×10^1
$^{244}_{95}\text{Am}$	B(S)	2.97×10^7	3.94×10^{-6}	7.41×10^{-5}	$^{252}_{98}\text{Cf}$	B(S)	6.43×10^2	6.42×10^{-12}	4.55×10^1
$^{242}_{96}\text{Cm}$	LIV(S)	3.32×10^3	1.20×10^{-10}	2.44	$^{253}_{98}\text{Cf}$	L(I)	2.87×10^4	7.65×10^{-10}	3.82×10^{-1}
$^{243}_{96}\text{Cm}$	B(S)	4.13×10^1	6.42×10^{-12}	4.55×10^1	$^{254}_{98}\text{Cf}$	L(I)	9.19×10^3	4.91×10^{-12}	5.95×10^1
$^{244}_{96}\text{Cm}$	B(S)	8.01×10^1	9.05×10^{-12}	3.23×10^1	$^{253}_{99}\text{Es}$	L(I)	2.58×10^4	6.13×10^{-10}	4.76×10^{-1}
$^{245}_{96}\text{Cm}$	B(S)	7.29×10^{-2}	4.67×10^{-12}	4.56×10^{-1}	$^{254\text{m}}_{99}\text{Es}$	B(S)	3.21×10^5	5.26×10^{-9}	5.56×10^{-2}
$^{246}_{96}\text{Cm}$	B(S)	2.21×10^{-1}	4.67×10^{-12}	1.38	$^{254}_{99}\text{Es}$	B(S)	1.07×10^3	1.90×10^{-11}	1.54×10^1

TABLE VI (cont'd)

Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H	Radio-nuclide	Critical Body Organ	Specific Activity ($\mu\text{c}/\mu\text{g}$)	(MPC) _c ($\mu\text{c}/\text{cc}$)	Relative Hazard H
$^{255}\text{Es}_{99}$	L(I)	1.71×10^4	4.09×10^{-10}	7.14×10^{-1}	$^{255}\text{Fm}_{100}$	L(I)	5.67×10^5	1.08×10^{-8}	2.70×10^{-2}
$^{254}\text{Fm}_{100}$	B(S)	3.67×10^6	$6.28 \times 10^{-8*}$	$4.65 \times 10^{-3*}$	$^{256}\text{Fm}_{100}$	L(I)	4.63×10^6	1.75×10^{-9}	1.67×10^{-1}

B - bone
 BT - body tissue
 KI - kidney
 L - lung
 LLI - lower large intestine
 LIV - liver
 PR - prostate
 SI - small intestine
 SK - skin
 SP - spleen
 ST - stomach
 TB - total body
 TH - thyroid
 ULI - upper large intestine
 (I) - insoluble
 (S) - soluble
 (Su) - submersion

*The correct values are given here, but values for Fm^{254} plotted in Fig. 3 are earlier values which were revised after the manuscript had been prepared for publication.

BIBLIOGRAPHY

1. K. Z. Morgan, W. S. Snyder and M. R. Ford, "Maximum Permissible Concentration of Radioisotopes in Air and Water for Short Period Exposure," Proc. of the International Conference on the Peaceful Uses of Atomic Energy, Vol. 13, pp. 139-158, United Nations, New York (1956).
2. P. Drinker and T. Hatch, Industrial Dust, Second Edition, McGraw-Hill Book Company, Inc., New York (1954).
3. F. Duhamel and J. M. Lavie, "Comment Établir des Règles Pratiques Pour Éviter la Contamination," Health Physics in Nuclear Installations, pp. 317-336, European Nuclear Energy Agency (May 25-28, 1959).
4. Recommendations of the International Commission on Radiological Protection, ICRP Publication 2, Report of Committee II on Permissible Dose for Internal Radiation, Pergamon Press, London, England (1959); "Report of ICRP Committee II on Permissible Dose for Internal Radiation (1959), with Bibliography for Biological, Mathematical and Physical Data," Health Physics Journal, Vol. 3, pp. 1-380 (June 1960).
5. "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," Publication of the National Committee on Radiation Protection, National Bureau of Standards Handbook 69, Supt. of Documents, U. S. Government Printing Office, Washington 25, D. C. (June 5, 1959).
6. D. M. Davis and W. D. Cottrell, a private communication to K. Z. Morgan (April 16, 1962).
7. "Regulations for the Safe Transport of Radioactive Materials," Safety Series No. 6, IAEA, Vienna (1961); "Regulations for the Safe Transport of Radioactive Materials - Notes on Certain Aspects of the Regulations," Safety Series No. 7, IAEA, Vienna (1961).
8. "Sanitary Regulations for Work with Radioactive Substances and Sources of Ionizing Radiation," AEC-tr-4612, issued October 1961 (translated from a publication of the State Publishing House of Literature on Atomic Science and Technology, Moscow, 1960).
9. "Maximum Permissible Concentration Values for the Transuranic Elements," to be published as a part of the report of the International Commission on Radiological Protection following the 1962 meetings in Stockholm, Sweden, and in Ottawa, Canada, ICRP Publication No. 6 (1963).