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Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water

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Subcommittee 9.	Protection Against Radiations from Radium, Cobalt-60, and Cesium-137 Encapsulated Sources.

With the increasing use of radioactive isotopes by industry, the medical profession, and research laboratories, it is essential that certain minimal precautions be taken to protect the users and the public. The recommendations contained in this Handbook represent what is believed to be the best available opinions on the subject as of this date. As our experience with radioisotopes broadens, we will undoubtedly be able to improve and strengthen the recommendations given in this report. In the meantime comments and suggestions will be welcomed by the committee.

One of the greatest difficulties encountered in the preparation of this Handbook lay in the interpretation of existing biological data dealing with the uptake and retention of radioactive materials by the body. Many variables are present in each experiment, and major discrepancies occur frequently between even the most reliable researches. A tremendous effort is presently being exerted to obtain a better understanding of the biological effects of radiation. In the 3 years, during which this report has been in preparation, so much progress has been made in the field that at times it has seemed almost hopeless to keep abreast of the changes. It is believed that the numerical values given in this report are such that errors, if any, will be in the direction of providing additional safety.

The present Handbook was prepared by the Subcommittee on Permissible Internal Dose. Its membership is as follows:

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Contents

Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water

A. Introduction

This is the first official published report of the Subcommittee on Permissible Internal Dose of the National Committee on Radiation Protection. It is the opinion of this Subcommittee that all unnecessary exposure to radioisotopes should be avoided. However, it is often impracticable, if not impossible, to prevent some radioisotopes from entering the body. Therefore, it is desirable to establish levels of maximum permissible exposure to serve as guides to safe operation and upper levels of exposure. In some cases there is considerable uncertainty about the maximum permissible values given in this report. However, because many persons are at present being exposed to certain of the radioisotopes, it is considered desirable to agree upon what are considered as safe working levels for these radioisotopes now rather than wait until more complete information is available. In this connection, it is well to bear in mind that persons may be exposed to radioisotopes for an indefinite period of time, perhaps a lifetime. Because, in general, it is impossible to predict at the start how long a person will be exposed, permissible limits must be set on the assumption that the occupational exposure will continue throughout the working life of the individual and environmental exposures will continue for a lifetime. The values given in this report have been derived on the basis of continuous exposures for a lifetime [1] or for the equilibrium condition in which the rate of elimination has become equal to the rate of deposition in the body in all cases except for Ra^{226}, Sm^{151}, and Pu^{239}. Therefore, their use as interim values for a period of several years is fully justified. If future information indicates that these

[1] The effective half-lives of the radioisotopes considered in this report, with the exception of Ra^{226}, Sm^{151}, Pu^{239}, and Sr^{90}, are so short that the time of exposure is not critical in the calculations and the same maximum permissible concentrations in air and in water are obtained regardless of whether the exposure is for 30 years of occupational exposure, 70-years lifetime, or an infinite period.

values should be more or less conservative, they can be adjusted before anyone has been unduly inconvenienced or before damage can be expected to result. In any case, because of the uncertainties involved in the present values and in determining the actual accumulation and potential hazard of radioisotopes in the human body, it is strongly recommended that exposure be kept at a minimum insofar as it is practicable. Bearing in mind that in the future it may become necessary to lower some permissible limits, it is suggested that a factor of safety that may be as large as ten be used in the design and operation of permanent installations where large quantities of radioactive material are involved. This is particularly important in cases in which provision of additional protection later would be very difficult and expensive.

The values of maximum permissible amounts of the various radioisotopes in the human body and of the maximum permissible concentrations of these radioisotopes in air and water as given in this report are chosen by this Subcommittee as the most acceptable values after considering a preliminary report to the Committee (giving values recommended by various radiation protection committees, as listed under section F of this report) and after making comparisons with values calculated by use of the data summarized in table 4. This report considers only a few radioisotopes, and particularly those that are of present-day interest. Other radioisotopes will be considered in subsequent reports when such information about them is needed and as data become available to serve as a basis of acceptance of safe recommended values. Likewise, values given in this report must be revised from time to time as more biological information is obtained.

Efforts should be made to prevent the accumulation of dangerous quantities of radioisotopes in the body. Radioisotopes may enter the body by way of food and water, in the air we breathe, through wounds and abrasions, and through pores of the skin. The physical state (liquid, solid, or gas) and the chemical form of the radioisotope help determine the type of radiation hazard and to some extent the degree of retention in the body and magnitude of hazard. Other important factors that determine the radiation hazard are the quantities of radioactive material involved, the facilities and equipment available for handling radioisotopes, the training and experience of those working with the radioactive material, and the respect they have for appropriate radiation protection standards and procedures.

B. Radioisotopes More Hazardous Inside the Body Than Outside

Radioisotopes when contained inside the body present greater hazards than when they are limited to external sources, for the following reasons:

1. They irradiate the body continuously until they are eliminated.
2. The biological half-life is very long for some radioisotopes, and in most cases it is difficult, if not impossible, to increase appreciably the elimination rate from the body.
3. Sources inside the body are in intimate contact with the body tissue. This enables alpha and low-energy beta radiation (which, because of limited range, do not present an external hazard) to reach radiosensitive tissue inside the body and to dissipate all their energy in a small volume of tissue inside a critical body organ.
4. It is very difficult to measure the amount and distribution of a radioisotope in the body, and even if such information is obtained, it is impossible to assess the hazard accurately. Methods of urine and fecal analysis have been developed for some radioisotopes, but most of these analyses are very tedious, time consuming, and expensive.

C. Methods of Estimating Maximum Permissible Amounts and Concentrations

There are various methods of estimating maximum permissible levels of radiation exposure, maximum permissible amounts of radioisotopes inside the body, and maximum permissible concentrations in air and water. Some of these methods are given in the following paragraphs.

1. Comparison with X-ray or γ-ray damage

We have had considerable experience for more than 50 years with these radiations, and the Subcommittee on Permissible Dose from External Sources of the National Committee on Radiation Protection has set the relative biological effectiveness (RBE) and the maximum permissible exposure to various types of radiation, as listed in table 1. The values in table 1 were accepted by the Chalk River, Canada, Conference (Sept. 29 and 30, 1949) and the International Commission on Radiological Protection meeting in London (July 1950).

TABLE 1.

Type	Relative biological effectiveness (RBE)	Maximum permissible weekly dose in the bloodforming organs [a]
X, γ	1	0.3 r/week.
β	1	.3 rep/week.
α	20	.015 rep/week.

[a] The values in this column as agreed on at the Chalk River and London Conferences apply specifically to the bloodforming organs. For the purpose of this report these values are extended to apply to all body organs but not the epidermal skin layer.

2. Comparison with radium damage

There have been many years of experience in which man could observe and study the damaging effects of X-rays and radium. The effects of external exposure to radium were observed shortly after the discovery of radium, as was also the case with X-rays;[2] and man's experience with radium fixed in the body dates back more than 25 years. The radium content of the body can be obtained by measurement of the gamma radiation from the body, by measurement of the radon exhaled from the body, and by autopsy measurements. The National Committee on Radiation Protection has set the maximum permissible amount of radium-226 in the body as 0.1 μc. The NCRP Subcommittee on Permissible Internal Dose has made the estimate that the chronic damage of Pu^{239} relative to Ra^{226} for equal energy absorbed is 2.5, and for acute exposure the damage of Po^{210} relative to Ra^{226} for equal energy absorbed is 20. Preliminary indications are that the biological effectiveness of Po^{210} relative to Ra^{226} is considerably less than 20 on the basis of chronic damage.[3] Care must be taken that comparisons with radium are made with only those elements that behave similarly in the body.

3. Comparison with background concentrations of naturally occurring radioisotopes in our bodies, in the air we breathe, and in the water and food we consume

For example, if a large group of people in one part of the world has 10 times the average content of radium in the body

[2] For example, Mr. Grubbé at Chicago, Ill., sought medical aid for an X-ray dermatitis on the back of his hand in January 1896, the same month Roentgen announced the discovery of X-rays. Becquerel received a radium burn a few years after he announced the discovery of radioactive radiations emitted by uranium, when he made the mistake of carrying a glass tube of radium-bearing barium chloride in his vest pocket for a few days.

[3] The RBE of Po^{210} with respect to Ra^{226} is taken as 5 in table 3, A, which is based on chronic exposures.

as the rest of the people in the world, and if this group of people has shown no detectable disadvantages, the conclusions could be that these higher concentrations would be safe as maximum permissible values.

4. Experiments with animals

Experiments on mice, rats, dogs, pigs, etc., are being conducted by many laboratories in order to determine the initial retention, the concentration in the various body organs, and the biological half-life of specific isotopes. Careful observations are made on both the living and sacrificed animals in order to detect damage to the various body organs. Studies are made of blood changes, tumor production, sperm counts, reduction in life span, etc. These results are extrapolated to man by giving more weight to the data from species that are closest to man.

5. Experience with Man

Experience with man will give the only completely reliable data, and even here the statistical variation is so great that data should be obtained for a large number of cases in order to obtain reliable results. For ethical reasons there is a limit to the data one can obtain by direct observations on man. However, very useful data have been obtained from observations on man following the accidental ingestion and inhalation of radioisotopes. For example, urinalyses of persons who have inhaled Pu^{239} and Sr^{90} owing to carelessness or accidents have furnished some of the best estimates of the biological half-life of these radioisotopes in man. Small tracer doses of some of the radioisotopes with short effective half-lives can be administered to man to obtain valuable information about the initial retention and biological half-life. In some cases short-lived radioisotopes can be substituted to obtain essential data concerning the behavior of more dangerous long-lived radioisotopes. For example, 5.8-day Ca^{47} can be used in place of the 152-day Ca^{45}, or the 9-day Po^{206} can be used in place of the 138-day Po^{210}.

D. Factors that Determine the Hazards of Radioisotopes

The factors that determine the hazards of the various radioisotopes are as follows:

1. Quantities Available

None of the radioisotopes except those occurring naturally presented problems until the age of high-voltage accelerators, nuclear reactors, and atomic bombs. From the stand-

point of common use and quantity available, I^{131}, P^{32}, Co^{60}, Sr^{90}, C^{14}, S^{35}, Ca^{45}, Au^{198}, Ra^{226}, Pu^{239}, and uranium present the major problems of irradiation inside the body.

2. Initial Body Retention

Large fractions of some elements such as iodine, strontium, and sodium are absorbed when they are taken into the body by any of the several routes and when available in their common chemical forms. In the case of elements like plutonium and uranium, only a small fraction is absorbed in the gastrointestinal tract. Therefore, the greater retention would increase the hazards from the first group as against those of the second. In dealing with the inhalation of radioisotopes, unless information specific to the radioisotope is available, it is assumed in the case of *soluble* compounds that 25 percent is retained in the lower respiratory tract. From this tract it goes to the blood stream, and a part of this goes to the critical organ within a few days. Fifty percent is held up in the upper respiratory tract and swallowed, so a fraction of that swallowed also reaches the critical organ. In the case of *insoluble* compounds, it is assumed that 12 percent is retained in the lower respiratory tract, which is usually taken as the critical organ when considering the inhalation of insoluble compounds. The rest is eliminated by exhalation and swallowing.

3. Fraction Going from Blood to Critical Body Tissue

Some elements in the blood stream are eliminated rapidly from the body, whereas large fractions of others are deposited in certain body organs.

4. Radiosensitivity of Tissue

Some body tissues are more radiosensitive than others. For example, the lymphatic tissue and bone marrow are much more radiosensitive than muscle or nerve tissue. Therefore, in equal concentrations an element like plutonium is more hazardous than uranium because the plutonium concentrates in the most sensitive part of the bone, whereas the uranium goes to other portions of the bone, the kidney, and various other relatively insensitive organs.

5. Size of Critical Organ

For a given number of microcuries of a radioisotope in a critical organ, it follows that the smaller the organ the greater the concentration and the greater the dose delivered

to the critical tissue. Iodine presents a much greater problem than sodium, since iodine is very selectively absorbed in a small body organ, the thyroid gland, whereas sodium is rather uniformly distributed throughout the body. In many cases the radioisotope is deposited in a large organ but localized in a small portion of that organ, so that, in effect, the mass of critical tissue may become very small.

6. Essentiality of the Critical Organ to the Proper Function of the Body

Some body organs are either not essential to the body function, or, when they are damaged or removed, special steps can be taken to supplement or compensate for their reduced function. It is for this reason that damage to the bone marrow, kidneys, eyes, etc., would represent perhaps a greater hazard than equal tissue damage to the thyroid gland.

7. Biological Half-life

Some elements like radium, plutonium, and strontium are deposited in critical body tissue where the rate of turnover is very slow or the biological half-life is many years. These radioisotopes are much more hazardous than radioisotopes like carbon, sodium, and sulfur (C^{14}, Na^{24}, and S^{35}), which have biological half-lives of a few days or weeks. The principal methods of elimination of radioisotopes from the body are by way of the urine, feces, exhalation, and perspiration. Usually elimination is much more rapid before the radioisotope is translocated from the blood to a more permanent area, such as the bone, than afterward. This time is usually of the order of a few days to a few weeks. After this initial period the elimination rate becomes more nearly exponential, and the application of the term "biological half-life" has real meaning.

8. Radioactive Half-lives of Intermediate Length

The mixture of $U^{238}+U^{234}+U^{235}$ that occurs in nature does not present much of a radiation hazard (if the radioactive daughter elements are removed); because with the very long, controlling half-life of U^{238} of 4.5×10^{9} years, it requires 1.5×10^{6} g of this uranium isotopic mixture to make up a curie of alpha activity. The maximum permissible amount of this mixture in the body (given in table 3,A) is 0.02 μc. This corresponds to about 0.03 g, and it is unlikely that a person would get this much uranium in his body.

If he did, it probably would result in a chemical hazard before the detrimental effects of radiation would show up. The U^{233}, with a half-life of 1.62×10^5 years (100 g/curie[4]), and Sr^{90}, with a half-life of 25 years (6.3×10^{-3} g/curie), are much greater hazards. In the case of Sr^{90} in equilibrium with Y^{90} the maximum permissible amount of Sr^{90} in the body is 1 μc, or only 6.3×10^{-9} g, which is about 10^{-13} of the mass of the human body. This concentration is so small and the rate of elimination so low once a maximum permissible amount of Sr^{90} in equilibrium with Y^{90} becomes fixed in the bone, that it is then very difficult, if not impossible, to make accurate estimates of the amount present. Therefore, if there is exposure to such radioisotopes, every precaution should be taken to minimize the body uptake, and urinalyses should be made frequently so that the amount going into the bone can be estimated from concentrations in the urine during the early portion of the period of exposure, when the elimination rate is much higher.

At the other extreme of specific activity, radioisotopes with very short half-lives do not present much of a hazard unless the exposure is maintained by continuous uptake, since the activity of such radioisotopes when deposited in the body soon decays to an insignificant level. As a rule-of-thumb one can remember that the activity is reduced to less than 1 percent after seven half lives ($2^{-7}=0.008=0.8\%$). Examples of these short-lived radioisotopes are P^{32}, with a half-life of 14.3 days (3.5×10^{-6} g/curie), and N^{16}, with a half-life of 7.35 sec (10^{-11} g/curie). In general, radioisotopes with intermediate radioactive half-lives of about 5 to 50 years present the greatest hazards, other factors being equal, and the danger diminishes for radioisotopes with greater or smaller radioactive half-lives. The most important period of exposure to laboratory personnel is from the age of 20 to 45, because very few younger persons are employed by laboratories that handle radioisotopes, so they are not frequently subject to large internal doses of radioisotopes; and many of the chronic effects of radiation do not manifest themselves until 15 to 25 years after the radiation insult (and $45+25=70$ years, which is the average life span). The younger the person who accumulates the radioisotopes in his body the greater the hazard and the more serious the accumulation of intermediate-lived radioisotopes like Pu^{239}, Ra^{226}, Sr^{90}, and Po^{210} in the body. It is for this reason that added precautions should be observed not to take into the body radioisotopes like Sr^{90} that might be translocated to

[4] g/curie$=7.66\times10^{-9}AT_r$, in which A=atomic weight, and T_r=radioactive half-life of the radioisotope in days.

the fetus; contaminated clothing should not be worn home, where it may present a radiation hazard to young members of the family; and dangerous quantities of radioisotopes should not be discharged into the air or into the public water supplies, where the population as a whole may be exposed. It is generally true also that fast-growing cells of the body are more subject to radiation damage than fully developed cells, and this is a good reason to be more cautious in permitting the accumulation of radioisotopes in young people or in women in the child-bearing age.

9. Energy of the radiation produced by the radioisotope

The radiation hazard associated with a radioisotope deposited in the body is proportional to the average energy of disintegration weighted for the biological effectiveness of the radiation. The total effective energy per disintegration of the Ra^{226} plus half [5] the energy of Rn^{222} and its alpha-emitting daughter products is 14.5 Mev. The energy per disintegration of Pu^{239} is 5.16 Mev, and so (on an energy basis alone) when equal curie amounts of Ra^{226} and Pu^{239} are deposited in the body, one would expect Ra^{226} to be about three times as hazardous as Pu^{239}. [Actually, it is thought that the fact that Pu^{239} is more densely concentrated in the radiosensitive portion of the bone than Ra^{226} more than compensates for this energy difference, so that the reverse may very well be true. The maximum permissible amount of Ra^{226} (in microcuries) in the body is taken to be about 2.5 times that of Pu^{239}.] Another interesting comparison is obtained by examining some of the beta- and gamma-emitting radioisotopes. In a comparison of H^3 with Na^{24} it is noted in table 4 that the effective energy per disintegration of H^3 is 0.006 Mev, and the effective energy per disintegration of Na^{24} is 2.7 Mev. On an energy basis alone the maximum permissible amount of H^3 in the body would be 450 times that of Na^{24}. In this case both Na^{24} and H^3 are assumed to be rather uniformly distributed in a similar manner throughout the body, so that the effective energy per disintegration is the principal factor determining the relative biological damage from these two radioisotopes when deposited in the body. The ratio of the maximum permissible amounts of the two radioisotopes in the body (using values from table 3, B) is approximately inversely proportional to the ratio of the effective energies.

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[5] Experiments of R. D. Evans have indicated that about half of the radon escapes from the body.

10. Specific ionization and attenuation of energy in tissue

As indicated in table 1, alpha particles are considered to be 20 times as damaging on an energy-absorption basis as beta or gamma radiation because of their high specific ionization. The specific ionization in air of a 1-Mev alpha is about 6×10^4 ion pairs per centimeter path, whereas that of a 1-Mev beta is only 45 ion pairs per centimeter path. It is considered that for most of the gross damaging effects of radiation the concentrated energy loss in tissue produced by an alpha particle represents a greater hazard by a factor of 20 than the less dense energy loss in tissue represented by the greater penetration of beta and gamma radiation.

Beta radiation is absorbed mostly in the immediate vicinity of the atoms from which it is emitted, while the attenuation of gamma radiation of the same energy is much slower (e. g., if a beta emitter has a maximum energy of 2 Mev, a negligible fraction of the beta rays has the maximum range in tissue of about 1 cm. In the case of a 2-Mev gamma emitter, only about 3 percent of the gamma-ray energy is absorbed in the 1 cm of tissue). Hence in a small organ most of the beta radiation emitted in the organ will be absorbed in the organ, whereas gamma energy emitted in the same organ will be absorbed in a much larger volume of tissue or escape from the body altogether. Alpha radiation is even more localized than beta. For example, almost all the energy of the 5.9-Mev alpha from At^{211} is absorbed in the thyroid gland, where it localizes. An alpha ray must have an enery of about 7.5 Mev to penetrate the epidermal protective layer of skin about the body, which has a minimum thickness of about 0.07 mm. The range of a 70-kev beta ray is about 0.07 mm of tissue, so only a small fraction of 70-kev beta rays will penetrate this protective layer. Therefore, hazards from alpha and low-energy beta radiation can be controlled by keeping alpha and low-energy beta sources outside the body.

E. Maximum Permissible Concentrations of Radioisotopes

Table 2 lists provisional levels of permissible concentrations of unknown mixtures of radioisotopes in the air and water beyond the areas that are under the control of the installation responsible for the contamination. These values are believed to be safe [6] for exposure to any of the radioisotopes for periods of a few months. Table 2 is intended

[6] Safe values of maximum permissible concentration of radioisotopes are considered not to produce any readily detectable biological damage.

for use as a provisional guide when only the gross activity is known. After essentially all of the activity has been accounted for, maximum permissible concentrations should be based on values given in table 3, using the method of appendix 1 if needed. However, if the gross activities are always sufficiently lower than the values in table 2,[7] it may not be necessary in practice for one to determine which radioisotopes are involved.

The values given in table 2 do not refer to natural backgrounds but to additions to the natural background, caused by man.

TABLE 2. *Provisional levels of permissible concentration of radioactive contaminants for use beyond the control area (Oct. 1951)*

Medium in which contained	β or γ emitter (μc/ml)	α emitter (μc/ml)
Air	10^{-9} (a)	5×10^{-12} (b)
Water	10^{-7}	10^{-7} (c)

Table 3 lists recommended values of maximum permissible amounts of radioisotopes fixed in the total body and maximum permissible concentrations of these radioisotopes in the air and water one may take regularly into the body. These values were selected by the Subcommittee on Permissible Internal Dose after examining recommendations of radiation protection committees, as listed in section F of this report, and comparing them with calculations from data given in table 4. In some cases there was considerable spread in these values. The spread in values from the various sources of reference was greater than a factor of 10 in a few cases, but usually not over a factor of 2 or 3. The first reference number after each maximum permissible value given in table 3 indicates the reference leading to the choice. Other references are given if the values do not differ by more than ± 50 percent. These uncertainties arise from the inconsistencies and voids in the biological data now available. Because of the many uncertainties involved, this Committee recommends that every effort be made to keep the concentrations of radioisotopes in air and water and in the body to a minimum. The goal should be *no* radioactive contamination of air and water and of the body if it can be accomplished with reasonable effort and expense. If such a goal cannot be attained, the average operating levels should be kept as far

[7] Only three radioisotopes, Ra ^{226}, Pu ^{239}, and Sr ^{90}, are known to have values of maximum permissible concentration less than those in table 2. The values in table 2 are considered safe for any of the radioisotopes if (a) is reduced to 0.2×10^{-9} for Sr ^{90}, if (b) is reduced to 2×10^{-12} for Pu ^{239}, and (c) is reduced to 0.4×10^{-7} for Ra ^{226}. See appendix 3.

below these recommended values as possible, and not above them for any extended periods of time. In many cases the values given in table 3 (and indicated by references G1 through G7 corresponding to the equation used) are calculated from the data in table 4. These calculated values assume uniform distribution within the critical body organ. However, uniform distribution never actually exists, and this is one of the reasons why a safety factor in applying the maximum permissible concentrations may be desirable and is suggested in the introduction to this discussion for applications that might lead to extensive contamination. The principle of the calculations has been to determine the uniform concentration of the radioisotope in the critical tissue that will irradiate it at a dose rate of (0.3/RBE) rep/week. The calculated values in table 3 are based on a continuous exposure, and in all cases except for Pu^{239}, Sm^{151}, and Ra^{226}, the effective half-lives are so short that the values have been calculated for an equilibrium period of exposure (see appendix 3).

In a few cases values are calculated for both soluble and insoluble compounds of the radioisotopes. Unless otherwise indicated, the values given in table 3 apply to soluble compounds. As more information becomes available, these calculations should be extended not only to other radioisotopes but to various compounds of each. Table 3 is divided for convenience into three parts. Part A applies to radioisotopes that are alpha emitters. Work with alpha emitters requires special ventilating equipment, special precautions to prevent the spread of contamination, and the use of monitoring instruments that are suitable to determine surface contamination and concentration of the contaminants in air and in water. When possible, separate laboratories should be set up for work with alpha-emitting radioisotopes and a separate section of the counting room should be devoted to alpha counting. Special waste processing and disposal facilities should be provided for work with the more dangerous alpha emitters.

Part B of table 3 lists beta- and gamma-emitting radioisotopes that are common elements in the body. They are listed as a group for two reasons: (1) they are of common interest to biologists and to medical people in many studies of living organisms, and (2) the maximum permissible concentrations of these radioisotopes can be estimated from a knowledge of the distribution and behavior of stable isotopes of the same elements in the body. Because the body is not an isotope separator, we can expect the radioisotopes to behave in the body in the same manner as the stable isotopes

of the same element, provided the average chemical forms are the same. The initial uptake, distribution, and biological elimination should be the same for the radioisotope as for the stable form of the same element. For example, equation H1 indicates that the biological half-life can be expressed as a function of the mass of the stable element in the critical organ, the daily intake of the stable element, and the fraction of the stable element taken into the body that reaches the critical organ. The critical organ is usually the organ of the body that has the greatest concentration of the radioisotope despoited in it. However, this is not always true because the biological half-life may be considerably different in various organs, and it is usually the total dose of radiation received by an organ that determines the principal damage from internal irradiation of radioisotopes. The critical organ should always be that organ that receives radiation damage that results in the greatest insult to the total body. Sometimes the critical organ may not be the one with the greatest concentration of the radioisotope or even the greatest local damage because of variations in radiosensitivity of the various body tissues and because some body organs are more vital to the existence of the whole organism. However, such cases are probably exceptional when dealing with chronic exposure.

Part C of table 3 lists other radioisotopes of interest because (1) they are commonly used in research, (2) they are commonly produced by nuclear reactors and accelerators, (3) they are among the more hazardous radioisotopes produced by nuclear reactors, (4) they are noble gases that escape from the reactors and associated operations, or (5) they are radioisotopes that are likely to be induced in water used for cooling a nuclear reactor.

Often a person is subject to radiation exposure from several different sources simultaneously. In any case, the maximum permissible concentration of radioisotopes in air and water and the external radiation should not exceed values that will permit an exposure of 0.3 rem/week to any part of the body except the epidermal skin layer. The maximum permissible dose to the basal layer of the epidermis (considered to be at a depth of 7 mg/cm^2) is 0.5 rem/week except in the case of the hands and forearms, where the maximum permissible value is 1.5 rem/week. A detailed discussion of how to treat the summation of exposures from various different radioactive sources is given in appendix 1.

The references in table 3, given in parentheses, refer both to radiation protection committees listed in section F and to general equations listed in section G. Nomenclature and

additional equations are given in section H. The μc and $\mu c/cm^3$ values for natural uranium given in table 3 refer to the natural mixture of U^{238}, U^{235}, and U^{234} separated from the other daughter products. In the case of Ra, Rn, Sr^{90}, Ba^{140}, Ru^{106}, Cd^{109}, Cs^{137}, and Ce^{144} the μc and $\mu c/cm^3$ values are based on the disintegration rate of the parent isotope only, but the effective energy of the daughter products is added to that of the parent after proper weighting for biological effectiveness. Table 4 gives some of the constants used in equations listed in sections G and H. In column 2 of table 4 the energy values followed by α are the effective energies in terms of alpha radiation and are given by the equation

$$\sum[E_\alpha + 1/20(bE)_\beta + 1/20(bE)_\gamma],$$

in which E_α, $(bE)_\beta$, and $(bE)_\gamma$ are the effective energies of alpha, beta,. and gamma radiation, respectively. In the case of Ra^{226} it was assumed that only half of Rn^{222} and its daughter products down to RaD^{210} were retained in the body. In the case of Rn^{222} in the body the effective energy in terms of alpha radiation of all the daughter products down to RaD^{210} is included. Much of the biological data given in table 4 is uncertain, and in many cases there are inconsistencies in the data available in the literature. The bibliography is a list of the references given in table 4. M. J. Cook and M. R. Ford, of Oak Ridge National Laboratory, assisted the Committee in collecting data used in these tables.

TABLE 3. *Maximum permissible amount of radioisotope in total body and maximum permissible concentration in air and water for continuous exposure (Oct. 1951)*

A. Common radioisotopes that are alpha emitters

Element	Organ (g)	Microcuries in total body [a]	Microcuries per milliliter of water [a]	Microcuries per milliliter of air [a]
Po^{210} (sol.)	Spleen, 150	0.02 (G4)	3×10^{-4} (G6)	2×10^{-10} (G5).
Po^{210} (insol.)	Lungs, 10^3	7×10^{-3} (G4)		7×10^{-11} (G5).
Rn^{226}+dr [c]	Body, 7×10^4		[f] 2×10^{-4} (G1)	
	Lungs, 10^3			10^{-8} (1,7).
Ra^{226}+½dr [c]	Bone, 7×10^3	0.1 (1,2,4,6,7)	4×10^{-8} (4,6,G6)	8×10^{-13} (6,7).
U-natural (sol.)	Kidneys, 300	0.2 (G5) [b]	7×10^{-5} (G6) [b]	1.7×10^{-11} (5,4) [b].
U-natural (insol.)	Lungs, 10^3	0.009 (G4)		1.7×10^{-11} (5,G5,4) [b].
U^{233} (sol.)	Bone, 7×10^3	0.04 (6)	1.5×10^{-4} (6)	1×10^{-10} (G5).
U^{233} (insol.)	Lungs, 10^3	0.008 (6,G4)		1.6×10^{-11} (6,G5).
Pu^{239} (sol.)	Bone, 7×10^3	0.04 (6,2)	1.5×10^{-4} (6)	2×10^{-12} (6).
Pu^{239} (insol.)	Lungs, 10^3	0.008 (G4)		2×10^{-12} (6,4).

See footnotes at end of table.

TABLE 3. *Maximum permissible amount of radioisotope in total body and maximum permissible concentration in air and water for continuous exposure (Oct. 1951)*—Continued

B. Beta- and gamma-emitting radioisotopes that are of interest because they are common body elements

Element and percentage in body [c]	Organ (g)	Microcuries in total body [a]	Microcuries per milliliter of water [a]	Microcuries per milliliter of air [a]
H^3 (HTO or H_2^3O), 10%.	Total body, 7×10^4.	10^4 (6,G4)	0.2 (G6)	2×10^{-3} (G5).
C^{14} (CO_2), 18%.	Fat, 10^4	250 (G4)	3×10^{-3} (G6)	10^{-6} (6,G7,4).
	Bone, 7×10^3	1,500 (G4)	4×10^{-3} (G6)	5×10^{-7} (G5).
Na^{24}, 0.15%.	Total body, 7×10^4.	15 (6,4,G4)	8×10^{-3} (6,G6,4)	2×10^{-6} (G5,4).
P^{32}, 1.0%.	Bone, 7×10^3	10 (2,6,4,G4)	2×10^{-4} (6,4)	1×10^{-7} (G5).
S^{35}, 0.25%.	Skin, 2×10^3	100 (6,G4)	5×10^{-3} (G6)	10^{-6} (4,G5).
Cl^{36}, 0.15%.	Total body, 7×10^4.	200 (G4)	2×10^{-3} (G6)	4×10^{-7} (G5).
K^{42}, 0.35%.	Muscle, 3×10^4.	20 (G4)	1×10^{-3} (G6)	2×10^{-6} (G5).
Ca^{45}, 1.5%.	Bone, 7×10^3	65 (G4)	5×10^{-4} (G6)	3×10^{-6} (G5).
Mn^{56}, 3×10^{-6}%.	Kidneys, 300	2 (G4)	0.15 (G6)	3×10^{-6} (G5).
	Liver, 1.7×10^3.	7.5 (G4)	0.3 (G6)	4×10^{-6} (G5).
Fe^{55} Fe^{59} 0.004%.	Blood, 5×10^3	1×10^3 (G4)	4×10^{-3} (G6)	6×10^{-7} (G5).
	Blood, 5×10^3	11 (G4)	1×10^{-4} (G6)	1.5×10^{-8} (G5).
Cu^{64}, 2×10^{-6}%.	Liver, 1.7×10^3.	1.5×10^2 (G4)	8×10^{-3} (G6)	6×10^{-6} (G5).
Zn^{65}, 0.003%.	Bone, 7×10^3	430 (G4)	6×10^{-3} (G6)	2×10^{-6} (G5).
I^{131}, 4×10^{-6}%.	Thyroid, 20	0.3 (6,G4)	3×10^{-4} (6,G6)	3×10^{-9} (6,G5).

C. Other radioisotopes of current interest

Element	Organ (g)	Microcuries in total body [a]	Microcuries per milliliter of water [a]	Microcuries per milliliter of air [a]
Be^7	Bone, 7×10^3	670 (G4)	1 (G6)	4×10^{-6} (G5).
F^{18}	Bone, 7×10^3	24 (G4)	0.9 (G6)	10^{-4} (G5).
A^{41}	Total Body, 7×10^4	30 (G4)	5×10^{-4} (G2)	5×10^{-7} (G3).
Sc^{46}	Spleen, 150	6 (G4)	0.4 (G6)	7×10^{-8} (G5).
V^{48}	Bone, 7×10^3	20 (G4)	0.5 (G6)	10^{-6} (G5).
Cr^{51}	Kidneys, 300	390 (G4)	0.5 (G6)	8×10^{-6} (G5).
Co^{60}	Liver, 1.7×10^3.	3 (G4)	2×10^{-3} (G6)	10^{-6} (G5).
Ni^{59}	Liver, 1.7×10^3.	39 (G4)	0.25 (G6)	2×10^{-5} (G5).
Ga^{72}	Bone, 7×10^3	8 (G4)	9 (G6)	3×10^{-6} (G5).
Ge^{71}	Kidneys, 300	67 (G4)	9 (G6)	4×10^{-5} (G5).
As^{76}	Kidneys, 300	10 (G4)	0.2 (G6)	2×10^{-6} (G5).
Rb^{86}	Muscle, 3×10^4.	60 (G4)	3×10^{-3} (G6)	4×10^{-7} (G5).
Sr^{89}	Bone, 7×10^3	2 (2, 6)	[d] 7×10^{-4}	[d] 2×10^{-6}.
$Sr^{90}+Y^{90}$ [e]	Bone, 7×10^3	1 (2, 6)	8×10^{-7} (6)	2×10^{-10} (6, G5, 4).
Y^{91}	Bone, 7×10^3	15 (G4)	0.2 (G6)	4×10^{-6} (G5).
Nb^{95}	Bone, 7×10^3	90 (G4)	4×10^{-3} (G6)	4×10^{-7} (G5).
Mo^{99}	Bone, 7×10^3	50 (G4)	14 (G6)	2×10^{-3} (G5).
Tc^{99}	Kidneys, 300	5 (G4)	3×10^{-2} (G5)	3×10^{-6} (G5).
$Ru^{103}+Rh^{103}$ [e]	Kidneys, 300	4 (G4)	0.1 (G6)	3×10^{-8} (G5).
Rh^{105}	Kidneys, 300	9 (G4)	1.5×10^{-2} (G6)	10^{-6} (G5).
$Pd^{103}+Rh^{103}$ [e]	Kidneys, 300	6 (G4)	1×10^{-2} (G6)	7×10^{-7} (G5).
Ag^{105}	Liver, 1.7×10^3.	18 (G4)	2 (G6)	10^{-4} (G5).

See footnotes at end of table.

TABLE 3. *Maximum permissible amount of radioisotope in total body and maximum permissible concentration in air and water for continuous exposure (Oct. 1951)*—Continued

C. Other radioisotopes of current interest—Continued				
Element	**Organ (g)**	**Microcuries in total body** [a]	**Microcuries per milliliter of water** [a]	**Microcuries per milliliter of air** [a]
Ag^{111}	Liver, 1.7×10^3.	36 (G4)	4 (G6)	3×10^{-5} (G5).
Cd^{109}+ Ag^{109m} [e].	Liver, 1.7×10^3.	40 (G4)	7×10^{-3} (G6)	7×10^{-8} (G5).
Sn^{113}	Bone, 7×10^3.	80 (G4)	0.2 (G6)	6×10^{-7} (G5).
Te^{127}	Kidneys, 300.	4 (G4)	3×10^{-2} (G6)	10^{-7} (G5).
Te^{129}	Kidneys, 300.	1.3 (G4)	10^{-2} (G6)	4×10^{-5} (G5).
Xe^{133}	Total body, 7×10^4.	300 (G4)	4×10^{-3} (G2)	4×10^{-6} (G3).
Xe^{135}	Total body, 7×10^4.	100 (G4)	1×10^{-3} (G2)	2×10^{-6} (G3, 4).
Cs^{137}+ Ba^{137m} [e].	Muscle, 3×10^4.	90 (G4)	1.5×10^{-3} (G6)	2×10^{-7} (G5).
Ba^{140}+La^{140} [e].	Bone, 7×10^3	5 (G4)	2×10^{-3} (G6)	6×10^{-9} (G5).
La^{140}	Bone, 7×10^3	24 (G4)	1 (G6)	10^{-6} (G5).
Ce^{144}+ Pr^{144} [e].	Bone, 7×10^3	5 (G4)	4×10^{-2} (G6)	7×10^{-8} (G5).
Pr^{143}	Bone, 7×10^3	29 (G4)	0.4 (G6)	7.5×10^{-7} (G5).
Pm^{147}	Bone, 7×10^3	120 (G4)	1 (G6)	2×10^{-7} (G5).
Sm^{151}	Bone, 7×10^3	420 (G4)	0.2 (G6)	10^{-9} (G5).
Eu^{154}	Bone, 7×10^3	22 (G4)	3×10^{-2} (G6)	6×10^{-9} (G5).
Ho^{166}	Bone, 7×10^3	17 (G4)	23 (G6)	3×10^{-6} (G5).
Tm^{170}	Bone, 7×10^3	19 (G4)	0.25×10^{-1} (G6)	5×10^{-8} (G5).
Lu^{177}	Bone, 7×10^3	78 (G4)	24 (G6)	5×10^{-6} (G5).
Re^{183}	{Thyroid, 20 {Skin, 2×10^3	35 (G4) 600 (G4)	8×10^{-2} (G6) 0.2 (G6)	8×10^{-6} (G5). 2×10^{-5} (G5).
Ir^{190}	Kidneys, 300.	21 (G4)	10^{-2} (G6)	7×10^{-7} (G5).
Ir^{192}	Kidneys, 300.	3.4 (G4)	9×10^{-4} (G6)	5×10^{-8} (G5).
Au^{196}	Kidneys, 300	10 (G4)	3×10^{-3} (G6)	1×10^{-7} (G5).
Au^{199}	Kidneys, 300	28 (G4)	7×10^{-3} (G6)	2.5×10^{-7} (G5).
Pb^{203}	Bone, 7×10^3	57 (G4)	0.1 (G6)	6.5×10^{-6} (G5).
At^{211}	Thyroid, 20.	6×10^{-4} (G4)	2×10^{-6} (G6)	3×10^{-10} (G5).
Th^{234}	Bone, 7×10^3	120 (G4)	3 (G6)	6×10^{-7} (G5).
Am^{241}	Bone, 7×10^3	0.056 (G4)	10^{-4} (G6)	3×10^{-11} (G5).
Cm^{242}	Bone, 7×10^3	0.05 (G4)	9×10^{-4} (G6)	2×10^{-10} (G5).

[a] References were considered to apply if the values agreed within ±50 percent. Calculated values were rounded off to one significant figure. The principal reference responsible for the choice of a particular value was listed first. The notations G1, G2, etc., refer to equations in section G and the single numbers to references in section F.

[b] Based on chemical toxicity. The microcurie and microcurie-per-milliliter values are given for the natural mixture of U^{238}, U^{235}, and U^{234} with all the other radioisotopes removed.

[c] Percentages of stable element by weight comprising total body. The other principal body elements, oxygen (65%), nitrogen (3%), and magnesium (4×10^{-2}%), are omitted because all their radioactive isotopes have very short half-lives.

[d] Obtained by a comparison of recommended values for Sr^{90} with the calculated values in the two cases.

[e] Values of microcuries and microcuries-per-milliliter are given for the parent element in equilibrium with its daughter element(s).

[f] This value actually applies to ingestion; although the submersion equation was used for the calculation, since it is considered that tissue in the gastrointestinal tract is submerged in a fluid. The equation for submersion was applied specifically to an element of tissue in the gastrointestinal tract that was surrounded by water contaminated with radon and its products and by other layers of tissue contaminated with such products.

In this case the total energy leaving the unit volume is approximately equal to the total energy absorbed in a unit volume, and one is justified in using this method of calculation, which gives 2×10^{-6} μc/ml of water. Approximately the same answer is obtained using the ingestion equation and the entire gastrointestinal tract as the critical organ.

If one is concerned with the case of submersion exposure due to a person or animal swimming continuously in the contaminated water, the value would be increased to about 2×10^{-4} μc/ml because in such a case the alpha radiation would not be effective and the value given here could be increased by a relative biological effectiveness of 20 and an energy ratio of 5.5.

F. Recommendations of Various Radiation Protection Committees

Reference numbers used in table 3:

1. Values agreed on by the Advisory Committee on X-ray and Radium Protection (1941).
2. Values agreed on by the Subcommittee on Permissible Internal Dose of the National Committee on Radiation Protection (Feb. 9 and 10, 1950).
3. Values agreed on at a meeting of some of the scientists in the United States who were interested in establishing interim values for the maximum permissible concentrations in air and water of some of the commonly used radioisotopes.
4. Values suggested by the Chalk River, Canada, Conference (Sept. 29 and 30, 1949). This was a meeting of representatives of the radiation protection committees of the United States, Great Britain, and Canada.
5. Values agreed upon at a meeting in Rochester, N. Y. (Sept. 27, 1949). This meeting was called by the University of Rochester Atomic Energy Project and members of the Atomic Energy Commission to discuss the toxicity data of uranium and to attempt to establish interim values for the maximum permissible concentration in air of soluble and insoluble compounds of uranium.
6. The International Commission on Radiological Protection at the Sixth International Congress of Radiology, meeting in London during July 1950, indicated as follows:

   > While the Commission does not, at the moment, consider that there is sufficient information to make firm recommendations concerning maximum permissible exposures to internal radiation from radioactive iostopes, it brings to the notice of users of radioactive isotopes values which are commonly used, at the present time, in the United States of America, Canada, and Great Britain.[8]

7. Values agreed upon by the American Standards Association, Subcommittee on Radium Dust, Radon Gas and Gamma Ray Exposure (Z–37, 1950).

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[8] Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units, 1950, NBS Handbook 47, p. 3 (June 29, 1951).

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(bE)$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_2'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
H^3	0.006	Total body D.	7×10^4 Ch1.	----	0.1 Hw1. Ch1.	250 G, Kl1.	4.6×10^3	19 •11 H1. Lm1, An1.	19 H4.	1.0 An2.	1.0 D.	1.0 D.	1.0 D.	0.75 H5.
Be^7	0.009	Bone Ha16, Ha23, Ha21, Ur2.	7×10^3 Ch1.	5	----	----	54.5	400 *Ha16*, Ha23.	48 *H4*.	<0.01 *Ur2*.	0.9 *Ha16*, Ha23.	0.35 Ha21, Ha23, Ur2.	3.5×10^{-4} H2.	0.09 H5.
		Fat G.	10^4 Ev1.	----	0.75 Ev1.	300 Ma1.	2.09×10^3	35 H1, Se1.	35 H4.	0.95 Ma1.	0.6 Ma1, H9.	0.5 H2.	0.5 G, Hw1.	0.36 H5.
C^{14}	0.053	Bone Sk2, Bl2, Bl1, He1, Sr1.	7×10^3 Ch1.	5	0.13 Ev1.	300 Ev1. Ma1.	2.09×10^3	180 Sk2.	180 H4.	0.95 Ma1.	0.07 Hw1, Ev1.	0.05 Na1, G.	4.8×10^{-2} H2.	3.6×10^{-2} H5.

F^{18}	0.24	Bone Gll, Evl, Shl.	7×10^{6}	------	1.2×10^{-4} Evl.	4.7×10^{-3} Sll, Hwl, Sml.	0.078	140 Gll.	0.078 H4.	1.00 Evl.	0.95 Shl.	0.1 H2.	0.1 Shl.	7.5×10^{-2} H5.
		Teeth Gll, Evl, Shl.	20	------	2×10^{-4} Evl.									
Na^{24}	2.7	Total body Bel, Bll.	7×10^{4} Chl.	30	1.5×10^{-3} H9, Hwl.	4 Mal, Evl, Shl.	0.62	29 Trl. ▲19 H1.	0.61 H4.	0.95 Hel.	1.0 D.	1.0 D.	0.95 H2.	0.73 H5.
P^{32}	0.68	Bone Kal, Lal, Hel, Ha2.	7×10^{5} Chl.	------	0.069 Mal.	1.4 Mal.	14.3	1,200 H1.	14 H4.	0.7 Hel.	0.92 Hel. ▲0.69 H9.	0.3 H2.	0.2 Hel, Atl.	0.2 H5.
S^{35}	0.055	Skin Ddl.	2×10^{5} Mal.	------	0.009 Shl.	1.3 Evl.	87.1	22 Tal. ▲120 H1.	18 H4.	0.56 Kal.	0.19 Shl. ▲0.1 H9.	0.14 Ddl.	0.08 H2.	0.074 H5.
Cl^{36}	0.26	Total body H8, Shl.	7×10^{4} Chl.	------	1.5×10^{-3} Hwl. Mal.	6.7 Mal. Evl.	1.6×10^{5}	29 H8. ▲ 11 H1.	29 H4.	0.95 H8.	1.0 H8.	1.0 H8.	0.95 H2.	0.73 H5.
A^{41}	1.78	Body	7×10^{4} Chl.	30	------	------	0.074	------	------	------	1 D.	------	------	------
K^{42}	1.59	Muscle Hll, Evl, Ntl.	3×10^{4} Chl.	30	0.003 Mal, Shl, Evl.	2.8 Shl, Evl.	0.52	33 H1.	0.51 H4.	0.9 Hel.	0.75 Hll, Evl. ▲0.37 H9.	------	0.7 H3.	0.53 H6.

See footnotes at end of table.

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*—Continued

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(\delta E)$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_2'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
Ca^{45}	0.085	Bone No1, He1, Be1, Pe1, Gr2, No2.	7×10^3 Ch1.		0.15 Ma1.	0.8 Ma1.	152	18,000 No2.	151 H4.	0.9 He1, Be1, Gr2.	0.99 Hw1, Gr2, Kl1. [a] 1.0 H9.	0.58 Pe1.	0.25 Gr2, No1, He1, Pe1, Be1. [a] 0.52 *H2.*	0.41 H5.
Sc^{46}	[a] 0.5	Spleen So6.	150 Ch1.	7			85	15 So6.	13 H4.	0.0005 So6.	0.04 So6.	0.03 So6.	1.5×10^{-5} H2.	7.5×10^{-3} H5.
V^{48}	0.54	Bone Ha16, So9.	7×10^2 Ch1.	5			16	50 Ha16, So9.	12 H4.	0.005 Ha16, So9.	0.5 Ha16, So9.	0.1 Ha16, So9.	5×10^{-4} H2.	0.025 H5.
Cr^{51}	0.01	Kidneys So1.	300 Ch1.	7	2.7×10^{-5} Uo1.	Trace Ma1.	26.5	110 So1.	22 H4.	0.05 G.	0.06 So1.	0.014 So1.	0.0007 H2.	0.004 H5.

Mn^{56}	1.1	Kidneys Sol, So6.	300 Ch1.	7	6×10^{-7} Ev1.	4×10^{-5} Mal.	0.108	2.5 So6. ▪ 78 H1.	*0.106* H4.	*0.05* Be1, Co1.	*0.09* So1, So6. ▪ 0.009 Ev1. ▪ 0.015 H9.	*0.08* So1, So6. ▪ 0.25 Co1, Gr1.	*0.004* H2.	2.2×10^{-2} H5.
		Liver Gr3, Co1, He1.	1.7×10^{3} Ch1.	10	1.7×10^{-6} Ev1, Hw1, Sh1.	4×10^{-5} Mal.	0.108	5 So6. ▪ 50 H1.	*0.106* H4.	*0.1* Gr3.	*0.16* Ev1. ▪ 0.015 H9.	*0.3* Gr1, Gr3, Co1.	*0.01* Gr3, Co1.	*0.09* H5.
Fe^{55}	0.006	Blood Ev1, Be1.	5×10^{3} Ch1.	------	5×10^{-4} Ev1.	0.012 Mal.	1.06×10^{3}	65 La1. ▪ 180 H1.	61 H4.	0.8 He1, La1.	0.64 Be1, Ev1. ▪ 0.8 H9.	1.0 D.	0.8 H2.	0.65 H5.
Fe^{59}	0.54	Blood Ev1, Be1.	5×10^{3} Ch1.	15	5×10^{-4} Ev1.	0.012 Mal.	46.3	65 La1. ▪ 180 H1.	27 H4.	0.8 He1, La1.	0.64 Be1, Ev1. ▪ 0.8 H9.	1.0 D.	0.8 H2.	0.65 H5.
Co^{60}	0.72	Liver Co1, Co2, Co5, He1.	1.7×10^{3} Ch1.	10	2×10^{-7} Ev1.	Trace Mal.	1.90×10^{3}	8.4 Co5.	8.4 H4.	0.2 Co1, Co5.	0.68 Ev1.	0.02 Co1, Co2, Co5, Gr1, Be1.	0.004 H2.	0.007 H5.
	0.55	Spleen Ev1.	150 Ch1.	7	4.7×10^{-7} Ev1.	Trace Mal.	1.90×10^{3}	9 Co5.	9 H4.	0.2 Co1, Co5.	0.14 Ev1.	0.00022 Co1, Co2, Co5.	4.4×10^{-5} H2.	7.7×10^{-5} H5.
Ni^{59}	0.05	Liver H8.	1.7×10^{3} Ch1.	------	Trace Mal.	Trace Mal.	9.1×10^{7}	8 G, H8.	8 H4.	0.2 H8.	0.68 H8.	0.02 H8.	0.004 H2, H8.	0.007 H5, H8.

See footnotes at end of table.

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*—Continued

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(\delta E)$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_3'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
Cu^{64}	0.11	Liver He1, Ha22, Sc1, Be1, Co6.	1.7×10^3 Ch1.	10	6×10^{-6} Ev1.	0.002 Ma1.	0.54	39 H1.	0.53 H4.	0.28 Co3, Co6.	0.08 Ev1.	0.33 Co3, Co6. [a] 0.13 Ha22.	0.09 Sc1, Ha22, Be1, Co3, Co6. H2.	0.13 H5.
		Eyes Tu1.	30 Ch1.	-------	2.4×10^{-6} Tu1.	0.002 Ma1.	0.54	21 H1.	0.53 H4.	0.28 Co3, Co6.	5×10^{-4} Tu1, H9.	0.0042 Co3, Co6.	1.2×10^{-3} H2.	0.002 H5.
Zn^{65}	0.085	Bone Sn2, He1.	7×10^3 Ch1.	5	1×10^{-4} Ev1.	0.017 Ev1, Sh1.	250	23 Sn2.	21 H4.	0.1 Sk1, G.	0.15 Sn1, Sn2.	0.15 Sn2.	1.5×10^{-2} H2.	4.5×10^{-2} H5.
Ga^{72}	0.8	Bone Du1, Du2, Du3, Du4, Pk1, Ha20.	7×10^3 Ch1.	-------	$<1\times10^{-6}$ Du1.	---------	0.59	2.4×10^3 Du2.	0.59 H4.	0.001 Du4, Pk1.	0.82 Du2.	0.4 Pk1, Du2, Ha20.	0.0004 H2.	0.1 H5.
Ge^{71}	[c] 0.01	Kidneys Ha21.	300 Ch1.	7	---------	---------	11.4	6 Ha21.	3.9 H4.	0.01 Ha21.	0.35 Ha21.	0.02 Ha21.	2×10^{-4} H2.	5×10^{-3} H5.

As^{76}	1.1	Kidneys Ht1, Sl1, Ha17.	300 Ch1.	7			1.12	37 Ha11. [a]124 Ha17.	1.09 H4.	0.03 Mo1.	0.02 Ht1, Ha17.	0.01 Dc1, Ht1, Ha17.	0.0003 H2.	2.7×10^{-3} H5.
Rb^{86}	0.73	Muscle Ha21.	3×10^{4} Ch1.	30			19.5	13 Ha21.	7.8 H4.	1.00 Ha21.	0.54 Ha21.	0.44 Ha21.	0.42 Ha21.	0.33 H5.
Sr^{89}	0.55	Bone Ha1, Ja1, Su1, Su2, He1, Be1, No1.	7×10^{3} Ch1.		6×10^{-5} Ma1, Uc1, Uc2.	3×10^{-4} Ha7, H8.	53	3.9×10^{3} H1. [a]18,000 H8, No2.	52 H4.	0.6 Ha1.	0.7 Ha1, Ha3, Ha4.	0.4 H2. [a]0.50 Su2.	0.25 H8. [a]0.42 H3.	0.22 H5.
$Sr^{90}+Y^{90}$	1.0	Bone Ha1, Ja1, Su1, Su2, He1, Be1, No1.	7×10^{3} Ch1.		6×10^{-5} Ma1, Uc1, Uc2.	3×10^{-4} Ha7, H8.	9.1×10^{3}	3.9×10^{3} H1. [a]18,000 H8, No2.	2.7×10^{3} H4.	0.6 Ha1.	0.7 Ha1, Ha3, Ha4.	0.4 H2. [a]0.50 Su2.	0.25 H8. [a]0.42 H3.	0.22 H5.
Y^{91}	[c]0.57	Bone Ha1, Ha7, Ha9, Ha10, Su2, Su4. Se3, Hd1, Ha18.	7×10^{3} Ch1.	5			57	>500 Ha1, Su4, Ha10, Ha9.	51 H4.	0.0005 Ha1. Ha7, Su2, Su3.	0.65 Ha1, Su4, Se3, Ha10, Ha9, Ha18.	0.55 Su3, Ha18.	2.8×10^{-4} H2.	0.14 H5.
Nb^{95}	[c]0.154	Bone Ha1, Ha7, Ha9, Ha10, Su3.	7×10^{3} Ch1.	5			35	50 Ha9.	21 H4.	0.45 Su3. [a]0.01 Ha1, Ha10, Ha9.	0.4 Ha9, Ha10, Ha1.	0.25 Ha9, Su3, H2.	0.13 Su3.	0.12 H5.

See footnotes at end of table.

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*—Continued

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(\bar{b}E)$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_2'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
Mo^{99}	0.22	Bone Co3, Co4, Ne1.	7×10^3 Ch1.	5	Trace Evl.	Trace Evl.	2.85	150 G.	2.8 H4.	0.7 Co3, Co4.	0.5 Co3, Co4.	3×10^{-4} H2.	0.0002 Ne1.	1.8×10^{-4} H5.
Tc^{99}	0.49	Kidneys Ha21.	300 Ch1.	7			4.3	4 Ha21.	2.1 H4.	0.5 Ha21.	0.1 Ha21.	0.005 Ha21.	2.5×10^{-3} H2.	2.5×10^{-3} H5.
$Ru^{106}+Rh^{106}$	1.4	Kidneys Ha1, Ha9, Ha10, So8.	300 Ch1.	7			365	20 Ha1, Ha9, Ha10.	19 H4.	<0.0005 Ha1, Ha9, Ha10.	0.04 Ha9, Ha1, Ha10.	0.04 Ha9, So8.	2×10^{-5} H2.	0.01 H5.
Rh^{105}	0.33	Kidneys So8.	300 Ch1.	7			1.52	28 So8.	1.4 H4.	0.2 H8.	0.08 So8.	0.05 So8.	0.01 H2.	1.7×10^{-2} H5.
$Pd^{103}+Rh^{103}$	0.074	Kidneys So8.	300 Ch1.	7			17	6 So8.	4.4 H4.	0.2 H8.	0.5 So8.	0.1 So8.	0.02 H2.	3.5×10^{-2} H5.
$Cd^{109}+Ag^{109m}$	0.04	Liver Ha21.	1.7×10^3 Ch1.	10			330	100 G.	77 H4.	0.0025 Ha21.	0.8 Ha21.	0.75 Ha21.	1.9×10^{-3} H2.	0.19 H5.
Ag^{105}	0.74	Liver So7.	1.7×10^3 Ch1.	10			45	3 So7.	2.8 H4.	0.02 So7.	0.1 So7.	0.006 So7.	1.2×10^{-4} H2.	1.6×10^{-3} H5.

Ag^{111}	0.37	Liver So7.	1.7×10^{3} Chl.	10			7.5	3 So7.	2.1 H4.	0.02 So7.	0.1 So7.	0.006 So7.	1.2×10^{-4} H2.	1.6×10^{-3} H5.
Sn^{113}	≈0.087	Bone Ha18, Ha19, Ha20.	7×10^{3} Chl.	5			112	72 Ha18.	44 H4.	0.0087 H2.	0.8 Ha18.	0.3 Ha18.	0.0026 Ha18.	0.076 H5.
Te^{127}	0.28	Kidneys Ha1, Ha9, Ha10, Ja2.	300 Chl.	7			90.4	15 Ha1, Ha9, Ha10, Ja2.	13 H4.	0.25 Ha1, Ha9, Ha10, Ja2.	0.2 Ha9.	0.06 Ha1, Ha9, Ha10, Ja2.	0.0007 Ha9, Ja2.	0.02 H5.
Te^{129}	0.89	Kidneys Ha1, Ha9, Ha10, Ja2.	300 Chl.	7			32	15 Ha1, Ha9, Ha10, Ja2.	10 H4.	0.25 Ha1, Ha9, Ha10, Ja2.	0.2 Ha9.	0.06 Ha1, Ha9, Ha10, Ja2.	0.0007 Ha9, Ja2.	0.02 H5.
I^{131}	0.22	Thyroid Ha1, Ke1, He1, Be1, Ho5, Ha25.	20 Chl.	3	5.2×10^{-4} Ma1, Ev1, Sh1, Hw1.	2×10^{-4} Ma1, Ba1, Ev1.	8	180 H1. ≈>30 Ha1.	7.7 H4.	1.00 Ha1.	0.2 Ha1, Ev1. ≈0.35 H9. ≈0.80 La1.	0.2 Ha1, Ha3, Ha4.	0.2 H2.	0.15 H5.
Xe^{133}	0.183	Body	7×10^{4} Chl.	30			5.27				1 D.			
Xe^{135}	0.562	Body	7×10^{4} Chl.	30			0.38				1 D.			
$Cs^{137}+Ba^{137m}$	0.57	Muscle Ha1, Ha9, Ha10.	3×10^{4} Chl.	30			1.2×10^{4}	17 Ha1, Ha9, Ha10.	17 H4.	1.00 Ha1, Ha10, Ha9.	0.45 Ha9.	0.48 Ha1, Ha9, Ha10.	0.48 H2.	0.36 H5.
$Ba^{140}+La^{140}$	1.06	Bone Do1, Ha9, Ha10, Ha1.	7×10^{3} Chl.				12.8	~200 Ha9. ≈>50 Ha1, Ha10.	12 H4.	0.1 Do1, Ha9, Ha1.	0.96 Do1, Ha9.	0.7 Do1.	0.07 H2.	0.2 H5.

See footnotes at end of table.

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*—Continued

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(\bar{b}\bar{E})$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_3'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
La^{140}	0.76	Bone Ha1, Ha9, Ha10.	7×10^3 Ch1.	5			1.67	35 Ha1, Ha9, Ha10.	1.6 H4.	0.003 Ha9, Cr2.	0.3 Ha1, Ha9, Ha10.	0.4 Ha9.	1.2×10^{-3} H2.	0.1 H5.
$Ce^{144}+Pr^{144}$	1.29	Bone Ha1, Ha10, Ha7, Hd1, Ha9, At2, Ha14.	7×10^3 Ch1.	5	Trace		275	500 Ha9, Ha1, Ha10.	180 H4.	0.0005 Ha1, Ha10, Ha9.	0.8 Ha14.	0.4 At2, Ha14.	2×10^{-4} H2.	0.10 H5.
Pr^{143}	0.31	Bone Ha1, Ha9, Ha10, Ha15, Ha16.	7×10^3 Ch1.	5			13.8	50 Ha15. [a]>100 Ha1, Ha9, Ha10.	11 H4.	<0.005 Ha1, Ha9, Ha10, Ha15.	0.6 Ha15, Ha1, Ha9, Ha10.	0.25 Ha15, Ha16.	1.3×10^{-3} H2.	0.063 H5.
Pm^{147}	0.067	Bone Ha1, Ha10, Ha24.	7×10^3 Ch1.	5			1.46×10^3	>100 Ha1, Ha10, 150 Ha24.	140 H4.	>0.0005 Ha1, Ha10.	0.7 Ha24.	0.35 Ha1, Ha10, Ha24.	1.7×10^{-4} H2.	0.09 H5.
Sm^{151}	0.02	Bone Ha18.	7×10^3 Ch1.	5			3.6×10^4	4.3×10^4 H8.	3.9×10^4 H4.	0.00014 H8.	0.65 Ha18.	0.2 Ha18.	2.8×10^{-5} H2.	0.05 H5.

Eu^{154}	0.366	Bone Ha17, Ha18, Ha15.	7×10^3 Ch1.	5			1.97×10^3	1400 Ha18, Ha15.	8.2×10^3 H4.	0.0005 H8.	0.7 Ha17.	0.35 Ha17, Ha18.	1.7×10^{-4} H2.	0.09 H5.
Ho^{166}	0.65	Bone So3.	7×10^3 Ch1.	5			1.14	37 So3.	1.1 H4.	[d] 0.12 So3. 0.0004 H2.	0.5 So3.	0.22 So3.	[d] >0.0001 So3. 0.027 H2.	0.07 H5.
Tm^{170}	0.32	Bone So6.	7×10^3 Ch1.	5			129	110 So6.	59 H4.	0.0005	0.92 So6.	0.7 So6.	3.5×10^{-4} H2.	0.18 H5.
Lu^{177}	0.14	Bone So3.	7×10^3 Ch1.	5			6.7	6 So3.	3.2 H4.	<0.0005 H8.	0.5 So3.	0.3 So3.	0.5×10^{-4} H2.	0.075 H5.
Re^{183}	0.09	Thyroid So2.	20 Ch1.	3			240	12hr So2.	0.5 H4.	0.5 H8.	0.005 So2.	0.0025 So2.	1.3×10^{-3} H2.	1.3×10^{-4} H5.
	0.003	Skin So2, So8.	2,000 Ma1.	0.1			240	5 So8.	5 H4.	0.5 H8.	0.8 So2, So8.	0.23 So2.	0.12 H2.	0.12 H5.
Ir^{190}	0.07	Kidneys So8.	300 Ch1.	7			10.7	23 So8.	7.3 H4.	0.2 H8.	0.15 So8.	0.05 So8.	0.01 H2.	1.75×10^{-2} H5.
Ir^{192}	<0.46	Kidneys So8.	300 Ch1.	7			70	23 So8.	17 H4.	0.2 H8.	0.15 So8.	0.05 So8.	0.01 H2.	1.75×10^{-2} H5.
Au^{196}	0.40	Kidneys El1, He1, Bt1.	300 Ch1.	7	Trace Ev1.	Trace Ev1.	2.69	50 G, H8.	2.6 H4.	0.1 El1.	0.06 Bt1.	0.24 He1, Bt1.	0.024 H2.	0.072 H5.
Au^{199}	0.14	Kidneys El1, He1, Bt1.	300 Ch1.	7	Trace Ev1.	Trace Ev1.	3.3	50 G, H8.	3.1 H4.	0.1 El1.	0.06 Bt1.	0.24 He1, Bt1.	0.024 H2.	0.072 H5.
Pb^{203}	0.12	Bone So8, Ev1, Au1, Kh1, Kh2.	7×10^3 Ch1.	5	2×10^{-6} Sl1, Ev1.	3×10^{-4} Sl1, Ev1, Kh2.	2.17	<730 Kh1.	2.16 H4.	0.15 Kh2, Kh3.	0.8 So8.	0.3 So8.	4.5×10^{-3} H2.	9.8×10^{-4} H5.

TABLE 4. *Constants for calculating maximum permissible internal concentration of radioisotopes*—Continued

1	2	3			4	5	6	7	8	9	10	11	12	13
Element	Effective energy,[b] $\Sigma(\delta E)$ Mev	Critical organ			Concentration of element per gram of organ	Daily intake of element by ingestion	Half-life			Fraction going from GI tract to blood, f_1	Fraction in critical organ of that in total body, f_2	Fraction from blood to critical organ, f_2'	Fraction reaching critical organ—	
		Organ	Mass	Effective diameter			Physical, T_r	Biological, T_b	Effective, T				By ingestion, f_w	By inhalation, f_a
			g	*cm*	*g*	*g/day*	*Days*	*Days*	*Days*					
Po^{210} (sol.)	5.3α	Spleen Fi2, Fi3, Hu2.	150 Ch1.	7	----	----	138.3	57 Hu2.	40 H4.	0.02 Fi2.	0.06 Fi5.	0.015 H2.	0.0003 Fi2.	0.004 H5.
Po^{210} (insol.)	----	Lungs Fi4.	10^3 Ch1.	----	----	----	138.3	40 Fi4.	31 H4.	----	1.0 D.	----	----	0.12 H7.
At^{211}	6.8α	Thyroid Ha25.	20 Ch1.	3	----	----	0.31	180 H8.	0.31 H4.	1.00 Ha25, H8.	0.2 H8.	0.07 Ha25.	0.07 Ha25.	0.05 H5.
Rn^{222}+ daughter products.	19.5α inside 3.6β,γ outside.	Lungs	10^3 Ch1.	----	----	----	3.83	----	----	----	1 D.	----	----	----
		Body	7×10^4 Ch1.	30										
Ra^{226}+ ½daughter products.	14.5α	Bone No1, Ge1, La1, He1.	7×10^3 Ch1.	5	1.7×10^{-14} Hu1.	7×10^{-13} Da1, Ly1, Hu1.	5.9×10^5	1.6×10^4 Si1. [a]7.9×10^3 H1.	1.6×10^4 H4.	0.2 Si1, No1, St1.	0.99 Ge1.	0.075 Si1.	0.015 H2, Si1, No1, La1.	0.026 H5.
Th^{234}	0.055	Bone Mt1, Ha8, Ha1.	7×10^3 Ch1.	5	----	----	24.1	4.3×10^4 H8. [c]>200 Ha1.	24.1 H4.	0.0005 Ha8, Ha1, Ho4. [a]0.00014 H8.	0.82 Ha8. [a]0.75 H8.	0.78 Ur1, Si1. [a]0.7 H8.	3.9×10^{-4} H2.	0.2 H5.

U, natural (sol.)	4.43α	Kidneys Ho2.	300	7	2×10^{-3} Vol.	2×10^{-6} Da1.	1.64×10^{12}	30 Ho2.	30 Ho2.	0.0005 Ha1.	0.065 Vo1.	0.33 Vo1.	0.0002 H2.	0.08 H5.
U, natural (insol.)	.....	Lungs Ho3.	10^{3} Ch1.	.....	.....	.....	1.64×10^{12}	120 Ho3.	120 H4.	.....	1.0 D.	.....	.....	0.12 H7.
U^{233} (sol.)	4.9α	Bone Ha1, Vo1, Ho2.	7×10^{3} Ch1.	5	10^{-4} Ly1.	2×10^{-6} Da1.	5.9×10^{7}	300 Ho2. [a]2.4×10^{4} H1.	300 H4.	0.0005 Ha1.	0.85 Vo1.	0.2 Ha1, Vo1.	10^{-4} H2.	0.05 H5.
U^{233} (insol.)	.....	Lungs Ho3.	10^{3} Ch1.	.....	.....	.....	5.9×10^{7}	120 Ho3.	120 H4.	.....	1.0 D.	.....	.....	0.12 H7.
Pu^{239} (sol.)	5.16α	Bone Ha1, Kt1, He1, Mi1, Pa1, Ln1.	7×10^{3} Ch1.	5	.....	.....	8.8×10^{6}	4.3×10^{4} Lm1.	4.3×10^{4} H4.	0.00014 H2, Ln1. [a]0.00007 Ha1.	0.75 Ha1, He1, Ln1, Ha3, Pa1.	0.7 Pa1.	0.0001 Kt1.	0.18 H5.
Pu^{239} (insol.)	.....	Lungs Ab1.	10^{3} Ch1.	.....	.....	.....	8.8×10^{6}	360 *Ab1.*	360 *H4.*	.....	1.0 D.	.....	.....	0.12 H7.
Am^{241}	5.45α	Bone Ha1, Ha10, Ha12.	7×10^{3} Ch1.	5	.....	.....	1.79×10^{5}	890 Ha13.	890 H4.	0.0005 Ha1, Ha10, Ha12, Ha13, Se2.	0.90 Ha13.	0.25 Ha13, Ha12, Ha1, Ha10.	1.3×10^{-4} H2.	0.063 H5.
Cm^{242}	6.08α	Bone Ha1, Ha19, So5.	7×10^{3} Ch1.	5	.....	.....	150	600 So5, Ha1.	120 H4.	<0.0005 Ha1, So5.	0.9 Ha19, So5.	0.25 Ha1, Ha19, So5.	1.25×10^{-4} H2.	0.063 H5.

[a] Values calculated but not used in final determination.
[b] The energy values followed by α are the effective energies in terms of alpha radiation.
[c] The contribution from the short-lived member of the isomeric pair has not been used in the calculation.
[d] The first value differs from the second because once the element enters the bloodstream it is eliminated from the bloodstream very rapidly.

G. General Equations

Some of the values given in table 3 were calculated from the equations given below. (See appendix 2 for a discussion of some of the assumptions made in deriving and using the equations.) The equation numbers to the right are used for references in table 3 to indicate which equations were used for a calculation.

1. For submersion in a radioactive fluid

$$(MPC)_m = \frac{2.6\times10^{-3}\, W \rho_m (P_m/P_t)}{\sum(bE)} \qquad \text{(G1)}$$

microcuries per milliliter of medium, m, to give W of continuous exposure during period of submersion in contaminated fluid.

$$(MPC)_w = \frac{0.8\times10^{-3}}{\sum(bE)} \qquad \text{(G2)}$$

microcuries per milliliter of water to give 0.3 rep/week of continuous exposure to beta or gamma during periods of submersion in contaminated water.

In this case we have set $\rho_m=1$ and $P_m/P_t \doteq 1.02$. For exposure to alpha radiation P_m/P_t would be set equal to about 1, and W in equation G1 would be taken as (0.3/20) rep/week.

$$(MPC)_a = \frac{1.8\times10^{-6}}{\sum(bE)} \qquad \text{(G3)}$$

microcuries per milliliter of air to give 0.3 rep/week of continuous exposure to beta or gamma during period of submersion in contaminated air.

In this case we have set $\rho_m=0.0012$ g/ml and $P_m/P_t \doteq 1/1.13$. For exposure to alpha radiation $P/_mP_t$ would be set equal to about 1/1.22, and W in equation G1 would be taken as (0.3/20) rep/week. Equation G3 is used in determining the maximum permissible exposure of a person to radioactive noble gases. If a noble gas that is a hard beta or gamma emitter is suspended in the atmosphere, the radiation dose a man receives from the gas in his lungs is negligible compared to the dose from a large cloud of gas surrounding him. The above equations are developed for 4π geometry and should be applicable to exposures to small organisms (such as fish eggs in water) or small organs (such as a man's ear when the man is surrounded by a radioactive gas). For general

exposure to a large body submerged in a radioactive fluid, the maximum permissible values given in the above equations may be doubled.

2. For radioisotopes inside the body or in the air and water taken into the body

$$q=\frac{2.6\times10^{-3}mW}{\sum(bE)f_2} \tag{G4}$$

microcuries in total body to give W exposure to the critical organ of mass, m.

$$(MPC)'_a=\frac{3\times10^{-8}qf_2}{Tf_a(1-e^{-0.69t/T})} \tag{G5}$$

microcuries per milliliter of air to give W exposure to the critical organ after the exclusive use of contaminated air for time, t.

In equation G5 the breathing rate was taken as 2×10^7 ml/day for a 24-hour day. For exposures of 8 hours' duration a day, the breathing rate would be taken as 10^7 ml/day.

$$(MPC)'_w=\frac{3\times10^{-4}qf_2}{Tf_w(1-e^{-0.69t/T})} \tag{G6}$$

microcuries per milliliter of water to give W exposure to the critical organ after the exclusive use of contaminated water for time, t.

In equation G6 the rate of water consumption is taken as 2,200 ml/day.

In the case of CO_2,

$$(MPC)'_a=Q/C\times\frac{(\text{ml of } CO_2)}{(\text{ml of alveolar air})}\times\frac{(\text{g of C})}{(\text{ml of } CO_2)}, \tag{G7}$$

in which $Q=\mu c/g$ of tissue to give W rep/week, and $C=$ concentration of carbon in critical organ. The London Conference made this substitution:

$$(MPC)'_a=(0.014/0.5)\times0.055\times0.0005=0.77\times10^{-6}\doteq10^{-6}. \tag{G7a}$$

Using the values in table 4 and equation G1:

$$(MPC)'_a=\frac{0.015}{0.75}\times0.055\times0.0005=0.55\times10^{-6}. \tag{G7b}$$

H. Nomenclature and Other Equations

The H numbers in parentheses are the reference numbers used in table 4.

b: $b=1$, for alpha radiation.

$b=1-e^{-(\mu-\sigma_s)x}$, for gamma radiation, where $(\mu-\sigma_s)$ is the total coefficient of absorption minus the Compton scattering coefficient of absorption in tissue (cm^{-1}), and x is the effective diameter of the organ in centimeters.

$b=0.33\,[1-(Z^{1/2}/43)]\,[1+(E^{1/2}/4)]$ for beta radiation, where Z is the atomic number of the radioisotope, and E is the maximum energy in Mev.

bE: effective energy of radiation per disintegration in Mev.

c: concentration of element in critical organ (element in grams/critical tissue in grams).

D: "definition", in table 4.

f_1: fraction going from gastrointestinal tract to blood.

f_2: fraction in critical organ of that in total body.

f_2': fraction going from blood to critical organ.

f_a: fraction retained by inhalation.

$f_a=(0.25+0.5f_1)f_2'$ for soluble compounds. (H5)

When f_2' is not known, the approximation is made for soluble compounds, $f_a \doteq (0.25+0.5f_1)f_2$. (H6)

$f_a=0.12$ for insoluble compounds when the lung is the critical organ. (H7)

f_w: fraction of soluble material reaching critical organ by ingestion $f_w=f_1f_2'$. (H2)

When f_2' is not known, the approximation is made for soluble compounds, $f_w \doteq f_1f_2$. (H3)

g: grams of any element in body$=mc/f_2$. (H9)

Values of g are given in the official Chalk River Report, September 29 and 30, 1949. These values must be considered as very tentative, since in some cases they do not agree with other published data.

G: "guess", in table 4.

I: daily intake of element, in g/day.

m: mass of critical organ, in grams.

MPC: maximum permissible concentration.

MPE: maximum permissible exposure.
P_m/P_t: relative stopping power in the medium compared to tissue.
RBE: relative biological effectiveness.
RBE=1, for beta and gamma radiation.
RBE=20, for alpha radiation, as indicated in table 1.
ρ_m: density of the medium in g/ml.
$\sum(bE)$: effective energy of radiation of both the radioactive isotope in question and its daughters, in Mev.
t: period of exposure (see appendix 3).
T: Effective half-life, in days

$$T=\frac{T_b T_r}{T_b+T_r}. \tag{H4}$$

T_b: biological half-life in days. When T_b is not known as a result of direct measurements, one may be able to calculate it by the equation

$$T_b=\frac{0.69mc}{If_w}. \tag{H1}$$

T_r: radioactive half-life, in days.
W: (0.3/RBE) rep/week.

When data are not available, direct comparisons are made of Sr with Ca, Th with Pu, Au with Cu, and Ni with Co, etc. Since data available for Cl are limited, it is considered to follow Na in the body. (H8)

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Appendix 1. Calculation of Values of Maximum Permissible Concentration of a Mixture of Radioisotopes

When a person is subject to several different sources of radiation simultaneously, the maximum permissible exposure (MPE) may be given approximately by the equation

$$\text{MPE}=a_1(\text{MPC})_A+a_2(\text{MPC})_B+\ \ldots\ +W_1(MPC)_A+W_2(MPC)_B+\ \ldots\ +e_1(\text{MPE})_x+\ \ldots\ +e_2(MPE)_n+\ \ldots \qquad \text{(K1)}$$

in which

$$a_1+a_2+\ \ldots\ +W_1+W_2+\ \ldots\ +e_1+e_2+\ \ldots\ =1. \qquad \text{(K2)}$$

a_1 = fraction of maximum permissible concentration of radioisotope A in air
a_2 = fraction of maximum permissible concentration of radioisotope B in air, etc.
W_1 = fraction of maximum permissible concentration of radioisotope A in water
W_2 = fraction of maximum permissible concentration of radioisotope B in water, etc.
e_1 = fraction of maximum permissible exposure per week to X-rays
e_2 = fraction of maximum permissible exposure per week to neutrons, etc.

For example, a person might be subject to fractions, a_1, a_2, etc., and W_1, W_2, etc., of the maximum permissible concentrations of radioisotopes as indicated in table 5 and at the same time receive the fraction, e_1, of the maximum permissible exposure to external gamma radiation.

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TABLE 5. *Example of exposures for calculation in appendix 1*

Source of exposure	Organ affected	Maximum permissible concentration in—		Fraction of maximum permissible concentration in—	
		Water	Air	Water	Air
Cu^{64}	Liver	$\mu c/ml$ 8×10^{-3}	$\mu c/ml$ 6×10^{-6}	W_1	a_1
Co^{60}	do	2×10^{-3}	10^{-6}	W_2	a_2
$Sr^{90}+Y^{90}$	Bone	8×10^{-7}	2×10^{-10}	W_3	a_3
Pu^{239}	do	1.5×10^{-6}	2×10^{-13}	W_4	a_4
Na^{24}	Total body	8×10^{-3}	2×10^{-6}	W_5	a_5
External γ	do	0.3 r/week		e_1	

In the example shown in table 5

$$(\text{MPE})_{\text{liver}}=a_1(6\times10^{-6})_{\text{Cu}}+a_2(10^{-6})_{\text{Co}}+a_5(2\times10^{-6})_{\text{Na}}+W_1(8\times10^{-3})_{\text{Cu}}+W_2(2\times10^{-3})_{\text{Co}}+W_5(8\times10^{-3})_{\text{Na}}+e_1(0.3)_\gamma, \quad \text{(K3)}$$

in which the fractions (a_1, a_2, a_5, W_1, etc.) can have any values less than 1, provided

$$a_1+a_2+a_5+W_1+W_2+W_5+e_1=1 \quad \text{(K4)}$$

$$(\text{MPE})_{\text{bone}}=a_3(2\times10^{-10})_{\text{Sr+Y}}+a_4(2\times10^{-12})_{\text{Pu}}+a_5(2\times10^{-6})_{\text{Na}}+W_3(8\times10^{-7})_{\text{Sr+Y}}+W_4(1.5\times10^{-6})_{\text{Pu}}+W_5(8\times10^{-3})_{\text{Na}}+e_1(0.3)_\gamma, \quad \text{(K5)}$$

in which the fractions can have any values less than 1, provided

$$a_3+a_4+a_5+W_3+W_4+W_5+e_1=1 \quad \text{(K6)}$$

$$(\text{MPE})_{\text{body}}=a_5(2\times10^{-6})_{\text{Na}}+W_5(8\times10^{-3})_{\text{Na}}+e_1(0.3)_\gamma. \quad \text{(K7)}$$

in which the fractions can have any values less than 1, provided

$$a_5+W_5+e_1=1. \quad \text{(K8)}$$

All the above equations must be satisfied before the radiation exposure to these sources is considered to be satisfactory. This is somewhat of an oversimplification of the problem, because some strontium and plutonium go to the liver and some chromium and cobalt go to the bone, and a gamma-emitting radioisotope in an organ of the body irradiates the whole body to some extent. However, this illustrates the principle upon which the values given in table 3 might be applied, and these errors in application are probably no greater than those in calculating the values given in table 3. Recent experiments have indicated that some of the organs of the body are interdependent in such a way that if half the midlethal dose is delivered to two organs,

it may produce greater damage than if the total midlethal dose is given singly to either of the organs. For example,[9] if albino rats are injected intraperitoneally with half-midlethal doses of P^{32} and Au^{198}, the mortality in 20 days is over 90 percent instead of the expected 50 percent. Most of the Au^{198} goes to the liver and spleen, whereas the P^{32} concentrates primarily in the bone. The supposition is that these organs are interrelated in such a way that simultaneous damage to the reticuloendothelial and hematopoietic systems results in gross body damage that is much greater than that which would result from twice the radiation insult administered separately to either system. There is no evidence that this synergistic effect is of importance when considering chronic damage resulting from extended exposures to concentrations of radioisotopes in the maximum permissible concentration range. However, the evidence of synergistic effects for acute exposure should lead to added caution when applying the MPC values to a mixture of radioisotopes extending over many years of exposure.

Appendix 2. A Discussion of Some of the Units Used and of the Assumptions Made in the Derivation of Equations in this Text

1. The rep as used here corresponds to an energy absorption in tissue of 93 ergs/g. This Subcommittee recognizes that the rep is not a generally accepted unit, and does not subscribe to the fundamental authenticity of any particular conversion value in ergs per gram of tissue.

2. The rem as used in this text corresponds to that amount of energy absorbed in tissue as a result of any type of ionizing radiation in the tissue that leads to the same biological damage as is produced by 1 roentgen. Again, the Subcommittee recognizes that the rem is not a generally accepted unit and uses it because of its convenience in appraising the hazard associated with exposure to various types of radiation in which the relative biological effectiveness (RBE) may differ from unity. By definition 1 rem = 1 rep/RBE. It is recognized that values of RBE are not well known and depend on many conditions involved in each individual case. However, because of the necessity of making an appraisal of the hazards associated with exposure to various types of ionizing radiation, the values of RBE as given in table 1 have been adopted.

3. The microcurie (μc) was assumed to correspond to 3.70×10^4 disintegrations per second. This value is used because of its general acceptance and because it has been recommended for use by an international committee on units.[10] In making comparison with radium it should be kept in mind that the best value for the number of disintegrations per second from 1 μg of radium is $3.608 \pm 0.028 \times 10^4$.[11]

4. The ratio of stopping power in tissue to the value in air used in the calculations is 1.13 for beta and gamma radiation and 1.22 for alpha radiation. These are average values in the energy ranges ordinarily involved here.

5. It is assumed that the radioisotope is uniformly distributed in the body organ. In many cases the distribution is far from uniform, and correction will be made in future calculations when experimental data become available.

[9] H. L. Friedell and J. H. Christie, The synergistic effect of P^{32} and colloidal Au^{198} on survival in male albino rats, NYO-1609.

[10] National Bureau of Standards Handbook 47. See footnote 8.

[11] F. Kohman, D. P. Ames, and J. Sedlet, The specific activity of radium, MDDC-852 (March 1947).

Appendix 3. Period of Exposure

The equilibrium period of exposure (when the rate of elimination becomes equal to the rate of deposition in the body) is given by the time, t, in equations G5 and G6 when the term $(1-e^{-0.69t/T}) \doteq 1$. This term is equal to 0.99 when $t=6.6\ T$, in which T is the effective half-life. This 99 percent of equilibrium is reached in a few months for most of the radioisotopes and in less than 20 years for all the radioisotopes listed in table 3, except Pu^{239}, Sm^{151}, Ra^{226}, and Sr^{90}, in which cases it is not reached until 780, 710, 290, and 49 years, respectively. The time of exposure used in the calculation of maximum permissible concentrations in air and water is not critical in most cases. In 70 years, assumed to be equivalent to a lifetime, Pu^{239}, Sm^{151}, and Ra^{226} will have reached 34, 36, and 67 percent respectively, of equilibrium body content.

In the case of occupational exposure of 8 hours per day (assuming half the daily consumption of air and water in the 8-hour work period), 5 days per week, and 49 weeks per year (considering time out for vacations, holidays, etc.), the values of maximum permissible concentrations of radioisotopes in air and water in the working area may be increased by a factor of 3 above those values listed in tables 2 and 3 [i. e., $2\times(7/5)\times(52/49) \doteq 3$]. In other words, the limited period of exposure for occupational workers reduces the need for the application of a safety factor. In the discussion in the Introduction a safety factor that might be as large as 10 was suggested. Therefore, the safety factor suggested for the maximum permissible concentration values given in tables 2 and 3, when applied to the working area of occupational workers with this limited period of exposure, would be reduced to 3.

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