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RADIATION PROTECTION

Recommendations of the International Commission on Radiological Protection

ICRP PUBLICATION 2

Report of Committee II

on

Permissible Dose for Internal Radiation

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REPORT OF COMMITTEE II ON PERMISSIBLE DOSE FOR INTERNAL RADIATION (1959)

I. INTRODUCTION

THE task of Committee II of the International Commission on Radiological Protection, ICRP, is to recommend values of maximum permissible body burden of radionuclides, q, and maximum permissible concentration of these nuclides, MPC, in air and in water (or food). These values are provided only for the more important radionuclides, and they are applicable primarily to occupational exposure. This Committee has recognized that such compilations are of limited usefulness unless periodically revised to incorporate the best available information and extended to include the values required by new developments and uses. It has worked closely with several of the national committees and in particular with the Internal Dose Committee of the United States National Committee on Radiation Protection, NCRP, in collecting these data and in making revisions of the earlier publications on internal dose published by the NCRP (1953)[1] and by the ICRP (1955).[2] In addition to revising and extending the earlier publications, the members of both committees hope that this publication will be a means of harmonizing and unifying the objectives and principles used by the international committee and by the various national committees in arriving at their decisions. The hope is expressed that the national internal dose committees will apply the same basic principles of radiation protection and will adopt the permissible exposure values recommended by the ICRP or will indicate the conditions and considerations which require their modification.

The basic recommendations concerning radiation exposure have been revised in recent years by the ICRP[3] and are reprinted in the present volume. Similar revisions have been made by the NCRP.[4] An examination of the 1958 Report of the ICRP reveals that the major changes of interest to Committee II are the following:

(1) Instead of a weekly limit, a quarterly limit is recommended thus giving greater flexibility for many operations.

(2) While the permissible quarterly rates are essentially comparable to former permissible rates, a limit on integrated dose is imposed in the case of exposure of the blood-forming organs and the gonads. The ICRP Recommendations[3] also apply the limit on integrated dose to the lenses of the eyes, but the relevant data are so inadequate the eyes are not considered as an organ of reference in this report.

(3) Explicit recommendations are given for some non-occupational groups and limits are suggested for the whole population.

A comparison of the present publication with earlier versions will reveal the very extensive modifications required by new data and methods of estimating internal dose, and will indicate that the number of radionuclides listed in the earlier publications has been increased by about a factor of three. All biological and physical data

used in the earlier versions have been reviewed, and the permissible exposure values have been revised accordingly. Refinements in the calculations for the exposure of the gastrointestinal tract and for chains of radionuclides in the body have resulted in new values for many of the permissible limits. The power function model is discussed in the Appendix as an alternative method of estimating the body burden for certain long-lived radionuclides. The data in the tables are expressed in terms of the exponential or compartment model for retention and elimination, but the maximum permissible concentration (MPC) and body burden values listed in the tables were selected after careful consideration by the Committee of the values obtained by the use of both models. While it is clearly impossible to be completely abreast of the literature in such a rapidly developing field, this revision probably represents the most important findings through 1957 as well as those in a few early publications of 1958.

All MPC values are given for a 40 hr work week as well as for continuous exposure, i.e. a 168 hr week. Previous editions of the internal dose publications gave values based on continuous exposure, partly because these same values sometimes were used, with an appropriate factor, to apply to cases of continuous non-occupational exposure and also because of variations in the actual work week. The values based on a 40 hr work week are included because they are directly applicable to the standard working conditions existing in many countries.

The values listed for continuous occupational exposure are convenient in obtaining permissible levels for special groups and for the population at large in accordance with the Report of the ICRP.[3] The appropriate factors to be applied in obtaining permissible levels for these groups are discussed in Sections II.3 and II.4. Because the continuous exposure values listed neglect several important considerations, particularly differences between children and adults, it should be emphasized that, even when corrected by the above factors, these can only be regarded as interim values for non-occupational exposure. It is hoped that the term "continuous occupational exposure values" will emphasize the provisional nature of their use for other purposes.

Although the data on which the MPC values are based are very incomplete and in some cases uncertain, they embody the latest and best research of hundreds of scientists, and it is believed that these MPC values are the best now available. They should serve as a guide to indicate whether the operational procedures used in practice are adequate to insure that the dose delivered by internally deposited radioactive material does not exceed the pertinent permissible limit set by ICRP.

For many radionuclides the radiation exposure period may last for many months or even a lifetime, although the intake may have occurred in a relatively short time. When radioactive contaminants are deposited in the body, it is often difficult to make an accurate estimate of the total body burden or of its distribution in the body. In most cases, even when the fact is established that a person carries a large internal burden of a radionuclide, little can be done to hasten its elimination from the body. According to one theory, any dose of ionizing radiation, no matter how small, may produce some genetic or somatic damage, and thus, it is considered wise to avoid all unnecessary exposure to radionuclides. This has been pointed out, also, by several national[5] and international[6] organizations. However, in the light of present

knowledge, occupational exposure for the working life of an individual at the maximum permissible values recommended in this report is not expected to entail appreciable risk of damage to the individual or to present a hazard more severe than those commonly accepted in other present day industries. The values given in this report are listed for occupational exposure and must be corrected by the application of appropriate factors for other uses, and in all cases the resultant tissue doses are intended to be in addition to those produced by the natural background and medical exposure.

II. BASIC STANDARDS OF MAXIMUM PERMISSIBLE INTERNAL EXPOSURE

1. Exposure categories. The ICRP[3] has made basic recommendations or suggestions concerning exposure to ionizing radiation for the following categories of exposure:

A. Occupational exposure.

B. Exposure of special groups:

(a) Adults who work in the vicinity of controlled areas (see paragraphs 71 and 72 of the ICRP Report,[3]) but who are not themselves employed on work causing exposure to radiation.

(b) Adults who enter controlled areas occasionally in the course of their duties, but are not regarded as radiation workers.

(c) Members of the public living in the neighborhood of controlled areas.

C. Exposure of the population at large.

In principle both the exposure of individuals and averages over the whole population have to be considered, but recommendations with regard to individual exposure are given only for the groups (A) and (B). Moreover, the ICRP considers that doses resulting from natural background radiation or individual doses resulting from medical and dental exposure are in addition to maximum permissible doses recommended in the report.

2. Occupational exposure (category (A). See paragraphs 46–52, *ICRP Report.*[3]) The basic rules concerned with occupational exposure due to internally deposited radionuclides are the following:

(a) The dose to the gonads or to the total body during any period of 13 consecutive weeks shall not exceed 3 rems. The dose to the gonads or to the total body at age N years shall not exceed $5(N-18)$ rems in case occupational exposure begins after age 18. If occupational exposure begins before age 18, the yearly dose before age 18 shall not exceed 5 rems and the dose to age 30 shall not exceed 60 rems.

(b) The effective RBE dose delivered to the bone from internal or external radiation during any 13 week period averaged over the entire skeleton shall not exceed the average RBE dose to the skeleton due to a body burden of 0.1 μc of Ra^{226}. This is considered to correspond to a dose rate of 0.56 rem/week in the case of Ra^{226} (derived from a dose rate of 0.06 rad/week, an RBE of 10 and $n = 1$). In computing the effective RBE dose to the skeleton, all absorbed energy shall be weighted by a relative damage factor, n. The relative damage factor, n, is taken as one for all energy absorbed from external radiation and for all internal emitters when the element taken into the body is an isotope of radium. If the isotope taken into the body is not an isotope of radium, the relative damage factor, n, is taken as 1 for all energy absorbed from X- or γ-radiation and as 5 for all other energy components,

whether they originate from the parent or the daughters it produces in the body. The effective energy is listed in Table 5 as $\Sigma EF(\mathrm{RBE})n$. For a more detailed discussion and examples, see Section IV.2 and V.1.

(c) The dose to any single organ of the body, excepting the gonads, bone, skin and thyroid, shall not exceed 4 rems in any 13 week period, or 15 rems in 1 year. The dose to skin and thyroid shall not exceed 8 rems in any 13 week period, or 30 rems in 1 year.

The decision of the ICRP[7] (1956) to set the average external occupational exposure at 5 rems/year (corresponding to 0.1 rem/week) is not applied to internal dose calculations except in the cases of radionuclides that are distributed rather uniformly throughout the body or are concentrated in the gonads. The purpose of limiting the average weekly total body dose (0.1 rem) to one-third of the former maximum weekly dose (0.3 rem) was to lessen the possible incidence of certain types of somatic damage, e.g. radiation induced leukemia and shortening of life span, which are considered to result primarily from total body exposure. Obviously, the reduction in the gonad dose was intended to lower the incidence of deleterious genetic mutations that will give rise to effects appearing in future generations.

Inasmuch as the restriction of integrated dose applies primarily to the total body and gonad dose, there is no basic change in the permissible RBE dose rate when individual organs[8] such as liver, spleen, bone, gastrointestinal (GI) tract and kidney are the critical body organs for reasons given in ICRP report paragraph 14.[3] It should be noted that the limits recommended here are maximal. In practice, the average occupationally exposed individual would receive a much lower dose.

Because the direct estimation of the body burden or of the dose to an organ or to the total body is generally difficult, and because in most cases measures to decrease the body burden are rather ineffective and difficult to apply, the only practical procedure for general protection of occupational workers is to limit the concentration of the various radionuclides in the water, food or air available for consumption. It is recommended, therefore, that:

(1) If there is no occupational external exposure, the concentration of a radionuclide or a mixture of radionuclides in air and in water which might be consumed by plant personnel during a 40 hr week be kept at levels not exceeding the appropriate MPC values given in this report. If there is occupational external exposure, the MPC values must be lowered to bring the total RBE doses within the limits prescribed by the basic rules. Thus, if D rem is the quarterly dose permitted to an organ by the basic rules and if external radiation delivers a dose E rem per quarter, then the MPC based on this organ must be reduced by the factor $(D-E)/D$. The calculation of an acceptable level for the case of a mixture of radionuclides is discussed in Section IV.8.

(2) Alternatively, over a period of 13 weeks, the concentrations of the various radionuclides present in air or in water may be allowed to vary, provided the total intake during any 13 week period does not exceed the total intake permitted by exposure at the constant levels indicated in subsection (1) above. It should be realized that while this method is in accordance with the basic recommendations its use is cumbersome, expensive and generally difficult, because it requires accurate and continuous monitoring of work areas and the keeping of detailed exposure histories for each individual. Its use is, therefore, only justified in exceptional cases.

The safest and simplest procedure to use in keeping within the basic limits (a), (b) and (c) in Section II.2 is to keep the level of contamination of the air, water or food consumed by plant personnel in the controlled area at or below the level indicated by the MPC values. These values are given for an exposure period of 40 hr/week and 168 hr/week. If a person's work assignments are such that he spends only 8 hr each week in the exposure area, the applicable MPC values are five times those listed for a 40 hr week in Table 1. However, this requires considerable care to determine that he is effectively unexposed during the remainder of his working week. If he spends 48 hr each week in the exposure area, the applicable MPC values are five-sixths of those listed for a 40 hr work week in Table 1. Similarly, when applied to food they generally will require modification to take account of the amount ingested. This is further discussed in Section IV.9.

Although the formula $5(N - 18)$ permits an average yearly dose to the total body and gonads of only 5 rems, the rules of the ICRP permit up to 3 rems during any interval (e.g. 1 min, 1 day, 1 week, etc.) provided that not more than 3 rems are received in any 13 consecutive weeks. Thus, an older person may receive up to 12 rems in a single year provided his dose does not exceed the limits prescribed by the formula $5(N - 18)$. Although flexibility is also allowed in principle for internal exposures, in practice it is risky and usually impractical to increase the MPC values much beyond those determined for operation over an extended period. The permissible levels do, however, take into account the exposure period (e.g. if the occupational exposures last for only 1 hr/week, the MPC values for a 40 hr week may be increased by a factor of 40), but if there are concurrent external exposures, the MPC must be reduced so that the total dose to any organ does not exceed the maximum permissible limits. In specific individual cases where sufficient monitoring is available (i.e. external monitoring meters, body fluid analyses, air surveys, etc.) and where no exposure has been received for the prior 13 week period, and if the restriction implied by the formula $5(N - 18)$ is not exceeded, a person may work for 1 hr where the concentration in air of an isotope with the total body as the critical organ is $40 \times 13 \times 12/5 = 1200 \times$ the $(\mathrm{MPC})_a$ values for the 40 hr week, but in such a case no further exposure shall be permitted in 13 weeks. This practice should be discouraged because of delays and inaccuracies in methods of estimating the body burden and dose to the organ from such an internally deposited radioactive material. However, if such exposures to contaminated air are unavoidable, the dose often may be reduced materially if appropriate and properly fitting masks are worn.

3. Exposure of special groups (category (B). See paragraphs 53–57, *ICRP Report.*[3]) The dose to the gonads or blood-forming organs of an individual belonging to either of the groups B(a) or B(b) shall not exceed 1.5 rems/year, and the corresponding limit for an individual of class B(c) is set at 0.5 rem/year. If no external radiation results due to operations within the controlled area, the corresponding MPC values for groups B(a) and B(b) are three-tenths of the occupational values for the 40 hr week, and for group B(c) are one-tenth of the occupational values for continuous exposure, i.e. for the 168 hr week. If external radiation results from operations within the controlled area and the dose due to this external radiation is E rems/year, then these values are to be reduced by the factor $(D-E)/D$ where $D = 1.5$ for groups B(a) and

B(b) and $D = 0.5$ for group B(c). The computation of the MPC for a mixture is discussed in Section IV.8.

If the radiation field (external and internal), does not irradiate significantly the gonads or the blood-forming organs, the MPC for an individual belonging to group B(c) shall be one-tenth the MPC value for continuous occupational exposure. Since the exposure of an individual belonging to group B(a) or group B(b) is directly related to his work in or near the controlled area, the MPC for such an individual shall be one-tenth the MPC for occupational exposure of an individual with the same work period per week. Thus, if the working period is 40 hr/week then the MPC for individuals of group B(a) and B(b) shall be one-tenth the MPC for the 40 hr week.

4. Exposure of populations (category (C). See paragraphs 58–68, *ICRP Report.*[3])

(a) Genetic and total body dose. The ICRP in its recent report[3] suggested limits on the *average* genetic dose to a population. These suggested limits are not considered as definitive but are offered for guidance in planning nuclear energy programs. Tentatively, allowing 2 rems to age 30 years for average genetic dose from man-made radiation (exclusive of medical exposures), 1.5 rems is suggested as a limit for internal dose and 0.5 rem as the limit for external dose to the gonads from such sources. Since the continuous occupational levels (168 hr/week) permit 5 rems/year × 30 years = 150 rems in 30 years to the gonads, such a continuous occupational MPC must be multiplied by a factor of 0.01 to give an equivalent constant level of exposure. The ICRP has suggested that the same dose limit (1.5 rems/30 years) and reduction factor (0.01) are to be applied when the total body is the critical organ. Except in a few cases, sufficient data for an estimate of gonad dose are lacking. In the absence of an MPC value based on the gonads, it is recommended that 0.01 of the MPC based on total body be used. The extent to which many of these nuclides contribute to the gonad dose is under investigation by the Committee.

(b) Somatic dose. For a radionuclide or mixture of radionuclides which does not have the total body or the gonads as critical organ, it is suggested that the average permissible level for large populations be one-thirtieth the continuous occupational value (168 hr/week) computed according to the basic rules (b) and (c) given in Section II.2 above. The Internal Dose Committee of ICRP and of several national organizations are studying the problem of the long-term effects of low-level exposure to the population at large with respect to somatic damage to the exposed individual, genetic damage to his children, ecological damage, etc.

III. MAXIMUM PERMISSIBLE VALUES FOR OCCUPATIONAL EXPOSURE

1. Assumptions and restrictions applying to maximum permissible exposure values in Table 1. The values of q and MPC for an individual will depend upon many factors such as his age, physical condition, eating habits and hygienic standards. They will depend also upon the physical and chemical properties of the radioactive material and the method of intake—by ingestion, by inhalation, through wounds or by absorption through the skin. The paucity of data concerning the effect of most of these factors does not warrant detailed treatment. To keep the required work and the size of this revision within manageable limits, and yet to meet the major needs of scientific and industrial users of isotopes, it has been necessary to limit severely the number

of factors considered. Therefore, MPC values are listed only for relatively insoluble and for the more common soluble compounds, and these compounds are specified only by the extent of solubility rather than by specific chemical structure. The only methods of intake considered are ingestion and inhalation except in a few cases—where submersion presents the greatest hazard criterion. All calculations are based on a "standard man" and thus do not provide for individual variations. The standard man is specified in Tables 6 through 11 and is a somewhat modified version of the standard man defined at the Chalk River Conference[9] (September 1949). This standard man is designed to represent a typical or average adult who is exposed occupationally.

Ideally, maximum permissible body burden, q, and maximum permissible concentration, MPC, should be based on studies of humans who have been exposed to and who have consumed a particular radionuclide under working conditions and over an extended period of time approximating those which are typical of the average occupational exposure. However, human data are very scarce and only in the case of radium does one have an accumulation of human experience for as long as 50 years, which is the minimum for selecting values for chronic exposure to man. Studies using total and partial body counters have been made recently to determine the uptake, distribution, and elimination of trace quantities of some radionuclides in the human body. In a few cases, certain radionuclides have been administered to humans therapeutically, and in some cases, accidents have occurred in which radionuclides have been taken into the body. The data from these cases of human exposure have been studied carefully and, where possible, such data are substituted in this report for earlier data based on animal experiments. For the majority of radionuclides, human data are lacking, and in such cases data from animal experiments must be extrapolated to man. Sometimes even animal data are not available and estimates are made from comparison with elements having similar chemical behavior. Recent studies of trace and minor stable element distribution in the human body[10] have been particularly helpful in these revisions. It is assumed that the normal stable element distribution in the various body organs is typical of the distribution that would result from chronic human exposure to radionuclides of these same elements and that the chemical form is similar. Likewise, a study of the metabolic balance between the trace and minor elements in the food, water, urine and feces of man has yielded direct evidence for the MPC of radionuclides of these elements. Because of the many assumptions and approximations made in applying much of the data in this publication, it is concluded that detailed refinements in the calculations generally are unwarranted.

In Table 1 are the recommended values of maximum permissible total body burden, q, and maximum permissible concentration in air, $(MPC)_a$, and in water, $(MPC)_w$, for about 240 radionuclides. The daily intake of water used in calculating $(MPC)_w$ includes the water content of food, and thus, consideration of the intake of a radionuclide in food is necessary only in case it concentrates in the food during processing or enters the food from other sources. In such cases the $(MPC)_w$ values of Table 1 converted to microcuries per gram are applicable when corrected for daily intake, i.e. to take account of the total intake of radionuclides in the complete diet. This publication includes values for all the radionuclides listed in the previous

publications of NCRP[1] (1953) and of ICRP[2] (1955) together with others for which a need has arisen and for which the necessary biological data are available. With few exceptions (e.g. certain daughter radionuclides and isomeric states), radionuclides with radioactive half-lives shorter than 1 hr are not considered in Table 1. The following are the principal assumptions and conditions which are the bases of the calculations.

(a) In all cases the values are listed both for soluble and for insoluble compounds (an exception is the case of some of the inert gases for which values are given only for the submersion of a person in the inert gas). The lowest values of $(MPC)_a$ and $(MPC)_w$ obtained are in bold-face type both for the soluble and insoluble forms of the isotope. The organs on which these values are based are termed the critical organs and are printed in bold-face type in Table 1.

(b) In all cases the values are computed for occupational exposure at the rate of 40 hr/week, 50 weeks/year for a continuous work period of 50 years, as well as for 50 years of continuous exposure, i.e. 168 hr/week.

(c) In all cases the calculated dose rate which determines the MPC takes into account the actual amounts of the radionuclide in the body or critical organ rather than an assumed state of equilibrium. The MPC values based on a critical organ are set by the requirement that the dose rate (rems/week) after 50 years of occupational exposure shall not exceed the values specified in (a), (b) and (c) of Section II.2. During a 50 year exposure period, equilibrium is reached for the vast majority of the radionuclides because the effective half-life is short compared to this work period (i.e. the term $e^{-0.693t/T}$ in equations (7) and (8) is approximately zero for $t = 50 \times 365$ days). Exceptions to this rule are listed in Table 2. Column 5 of Table 2 gives the effective half-life, and column 6 gives the percentage of equilibrium the body burden attains over a period of occupational exposure lasting 50 years. Most of these exceptions are in the $5f$ type rare earth group of elements which are assigned a biological half-life of 200 years. The extreme case is represented by ten of these radionuclides which reach only 16 per cent of equilibrium in the body in 50 years of occupational exposure.

(d) In the case of a radionuclide which decays to form radioactive daughters, the calculation assumes that only the parent radionuclide enters the body, but the estimated dose rate includes all the energy released by the daughter elements formed in the body. There are two exceptional cases, Rn^{220} and Rn^{222}, where a state of equilibrium typical of that attained in ordinary air is assumed. These cases are discussed further below. In all other cases, it is assumed that only the parent element enters the body. Because the various daughter elements generally have different effective half-lives, the percentage of equilibrium attained is generally not the same for all elements of a chain. Also, the effective energies, i.e. the weighted energy absorbed per disintegration, are not the same for different members of the chain, so that the dose rate after 50 years exposure will generally not be the same percentage of the dose rate resulting from an equilibrium body burden as the figure shown in Table 2. Thus, for radionuclides which decay to form radioactive daughters these percentages give only a rough indication of the percentage of equilibrium dose rate attained at the end of 50 years.

(e) The assumptions and formulas are presented in terms of a compartment

model, i.e. each organ is assigned a biological half-life, and the radionuclide that accumulates in the organ is considered to be eliminated at a constant rate. In general, this is a drastic oversimplification of the situation since the organ retention usually requires several exponentials, or perhaps a power function, for its mathematical representation. Unfortunately, the biological information available generally does not yield detailed information on organ retention, particularly for the conditions and periods of exposure of interest here. In selecting MPC and body burden values, the Committee has considered both multiple exponential and power function models for retention when such information is available, and the values finally selected are in some cases chosen between those calculated by these models. In view of the large measure of uncertainty in many of these cases, and in the interest of uniformity and economy of presentation the biological data in the Tables are given in terms of a single compartment model for each organ considered, with a biological half-life for each. The values of these are selected to produce in 50 years of constant level exposure the retention indicated by the more detailed model, and thus may not represent accurately the situation for short-term exposure. A discussion of the power function model and a table of the necessary parameters for its use are given in the Appendix.

(f) If occupational exposure continues beyond 50 years, the dose rate will continue to rise in the case of the radionuclides listed in Table 2 because they are not in a state of equilibrium under the assumed conditions, but for the radionuclides not listed in Table 2 the maximum permissible dose rate would not be exceeded. However, since the period of occupational exposure probably will not greatly exceed 50 years, and since the maximum permissible body burden, q, would be reached only after 50 years of occupational exposure at the MPC values given in Table 1, the average dose rate over the working life of the individual will be well below the maximum permissible dose rate, even for the isotopes in Table 2. While noteworthy, this observation does not alter the fact that the terminal dose rates would be in violation of the criteria adopted in (a), (b) and (c) of Section II.2, although the integrated dose undoubtedly would be considerably less than that permitted for many radionuclides not listed in Table 2. In the previous publications,[1, 2] the calculations were based on a 70-year exposure. Although this change to an exposure period of 50 years has had very little effect on the MPC values (i.e. a maximum increase of 27 per cent in the MPC values for some of the radionuclides in Table 2), it is believed that this change should be made in the calculations because, for most workers in atomic installations, the working period extends from age 18 to age 65 or less.

(g) The average breathing rate is 10^7 cm^3 per 8 hr work day; this is one-half the air breathed in 24 hr.

(h) The average rate of water consumption is 1100 cm^3 per 8 hr work day; this is one-half the water consumed in 24 hr.

(i) The dose from inert gases with radiation of sufficient energy to penetrate the minimal epidermal layer (7 mg/cm^2) results from external exposure to the surrounding cloud of radioactive gas rather than from the amount of gas in the body.

(j) In general, chemical toxicity is not considered in estimating the body burden or MPC values. However, in the case of uranium, the chemical toxicity has been considered and is the limiting criterion for the longer-lived nuclides of uranium.

2. Units of ionizing radiation used in Table 1. In Table 1 the units are the microcurie (μc) and microcurie per cubic centimeter (μc/cm^3) for maximum permissible quantities of the various radionuclides in the total body, q, and for the maximum permissible concentrations, $(MPC)_a$ and $(MPC)_w$, in air and in water, respectively. One curie is a quantity of a radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10}; the microcurie then, is one-millionth of this amount. In accordance with long established usage, however, the curie of natural uranium is considered to correspond to 3.7×10^{10} dis./sec from U^{238}, 3.7×10^{10} dis./sec from U^{234}, and 1.7×10^8 dis./sec from U^{235}. Also, the curie of natural thorium is considered to correspond to 3.7×10^{10} dis./sec from Th^{232} and 3.7×10^{10} dis./sec from Th^{228}. The rem is the unit of RBE dose of ionizing radiation in tissue. When a dose is expressed in rems it is superfluous to call it RBE dose. Therefore the unqualified term "dose" alone is used in such cases. The rem corresponds to the dose in tissue which results in biological damage equivalent to that produced per rad of X-radiation (of about 200 kV) having a linear energy transfer, LET, to water of 3.5 keV/μ, i.e., rem = RBE $\times$ rad. The rad corresponds to an energy absorption of ionizing radiation of 100 ergs/g in any medium. In this case the energy absorption is in tissue. The relative biological effectiveness, RBE, in this report is taken as one for β-, γ- and X-radiation, and conversion electrons (for low energy β-emitters, i.e. $E_m \leqslant 0.03$ MeV, the RBE = 1.7), 10 for α-particles, and 20 for recoil atoms. The reader is referred to the Handbook by the International Commission on Radiological Units for detailed information on units.[11]

3. Critical body organ. The values of body burden, q, in column 3 of Table 1 are based on that amount of the radionuclide which is deposited in the total body and produces the maximum permissible RBE dose rate to the body organ listed in column 2. The concentration values in water (columns 4 and 6) and in air (columns 5 and 7) are in turn based on the intake by the standard man who accumulates this body burden as a consequence of occupational exposure for a period of 50 years. In most cases, significantly different values of body burden result when effects on different organs are considered. The critical organ is considered to be that organ of the body whose damage by the radiation results in the greatest damage to the body. It is readily apparent that many factors must be considered in determining which affected organ will cause the body to suffer the greatest damage. Criteria of prime importance are: (a) the organ that accumulates the greatest concentration of the radioactive material; (b) the essentialness or indispensability of the organ to the well-being of the entire body; (c) the organ damaged by the route of entry of the radionuclide into the body; and (d) the radio-sensitivity of the organ, e.g. the organ damaged by the lowest dose. Theoretically all of these considerations are taken into account through the use of the RBE factors and the basic standards (a), (b) and (c) of Section II.2, but it is apparent that the information they represent does not embody much detail on most of the above criteria. Actually, except for a few radionuclides, case (a) above is the determining factor in choosing the critical body organ. For this revision, each radionuclide was studied individually. For some radionuclides as many as twelve reasonable choices of a critical organ were made with the corresponding permissible body burden and concentration values calculated for each organ. These

are listed in Table 1 with the critical organ (or organs in the case of identical MPC values) and minimal MPC values in bold-face type. For each isotope the MPC values are listed first for soluble materials and then for insoluble materials. The values for soluble materials are ranked according to magnitude of $(MPC)_w$ so that the first line in this group designates the critical organ determined solely on the basis of $(MPC)_w$. The values for insoluble materials are ranked according to the magnitude of $(MPC)_a$. The rankings based on $(MPC)_a$ and on $(MPC)_w$ may differ in some cases, so the smallest MPC in each group is in bold-face type to indicate it as a maximum permissible occupational exposure level for plant operation under the stated conditions. The MPC values for other additional organs (termed organs of reference in Table 1) are given primarily as an aid in estimating MPC values for mixtures of radionuclides, and thus, are not permissible levels for the single radionuclide unless in bold-face type.

The total body is listed as an organ of reference for all nuclides except a few of the inert gases. These values are included primarily as an aid in computing MPC values for mixtures, and as a check on the oversimplified model used. As mentioned in (e) on p. 8, this one compartment model is selected to represent the long-term retention in the critical organ and may not represent adequately the situation in other organs. For example, radium and strontium are long-term bone-seekers, but during the first day or two following ingestion appreciable amounts are present in the plasma and soft tissues. This amount is negligible so far as the 50 year accumulation in the bone is concerned, but a check is necessary to determine that the whole body limit is not exceeded by the amount present in the plasma and soft tissues. When present in a mixture, perhaps with other isotopes that concentrate primarily in the soft tissues, the dose delivered by this component of the total retention should not be neglected. The MPC based on total body also supplies a ready means of estimating the integrated dose, i.e. the dose to the body as a whole. While the basic rules do not directly limit the integrated dose except in the case of whole body irradiation, it is of considerable interest. Because the total body limit for constant level exposure is based on 5 rems/year (0.1 rem/week), the total body is sometimes the critical organ. Because the GI tract often receives a greater absorbed dose than any other body organ, and is frequently the critical organ for exposure to mixed fission products, it is with few exceptions included as an organ of reference for the radionuclides in Table 1.

IV. CALCULATION OF MAXIMUM PERMISSIBLE EXPOSURE VALUES

1. Basis for estimating maximum permissible exposure values. As indicated in the above discussion of the basic standards for maximum permissible internal exposure, two somewhat different criteria commonly are used in determining maximum permissible exposure values: (a) for bone-seeking radionuclides such as Sr^{90}, Pu^{239}, etc., which emit significant amounts of particulate radiation, the estimate is based on a comparison with Ra^{226} and daughter products; and (b) for all other radionuclides, the MPC and body burden values are set to limit the weekly RBE dose received by the various organs of the body*, e.g. 0.1 rem/week to the gonads and total body, 0.6 rem/week to the skin and thyroid, and 0.3 rem/week to all other soft tissues. Thus, for a

* In the case of long-lived radionuclides of uranium, the toxic effects set the limiting body burden.

bone-seeker, such as Sr^{85}, which emits only γ- or X-rays, the calculation must be based on 0.3 rem/week since the adjacent soft tissues are also irradiated to approximately the same extent as bone. The first method is the result of a calculation designed to determine, (i) the amount (μc) deposited in the bone that will deliver the same effective RBE dose as delivered by 0.1 μc of Ra^{226} and its daughter products and (ii) the amount (μc) deposited in the bone that will result in damage comparable to that observed from known deposits of Ra^{226} in the bone. In some cases, this first method rests on rather extensive clinical experience or studies of biological damage, either with the particular radionuclide, or with another radionuclide having similar chemical properties and similar metabolic behavior in the body. The method based on RBE dose rate is used generally when bone is not the critical organ or when direct experience is not available. The biological evidence supporting the limits on RBE dose to the various organs of the body is less direct than clinical observation or studies of biological damage, but is consistent with general experience involving radiation from both external and internal sources.

2. Body burden based on comparison with radium. In the case of α- and β-emitting radionuclides that localize in the bone, the maximum permissible body burden, q, is determined from a direct comparison with Ra^{226}. In 1941 an advisory committee[12] to the National Bureau of Standards first established the maximum permissible body burden for radium at 0.1 μg ($\sim$ 0.1 μc). Man has had years of experience with radium, which is the basis of reference in choosing the maximum permissible body burden of similar radionuclides that are deposited in the bone. The radium dial painters, patients treated medically with radium and persons using public water supplies relatively rich in radium[13] have furnished the best source of continuous human exposure from which to observe the effects of an internally deposited radionuclide. From autoradiographic studies[14] of human autopsy material, radium is known to be unevenly distributed in the bone, but other bone-seeking radionuclides may be even less uniformly distributed.[15] From animal experiments[16] it is known that some bone-seeking radionuclides produce greater damage to the bone than Ra^{226} for the same RBE dose. This greater damage is attributed to several factors, some of which are (a) non-uniform distribution, (b) greater radiosensitivity of the portion of bone in which the isotope is deposited, and (c) greater essentialness of the damaged tissue. Therefore a relative damage factor, n, is introduced into the MPC calculation to make some allowance both for the greater relative effectiveness of some radionuclides as well as for the fact that many have a more heterogeneous distribution in bone than radium. The relative damage factor, n, in the formula for effective energy, $\Sigma E_i F_i\,(\mathrm{RBE})_i n_i$ is taken as one provided (a) the parent element of the chain considered is an isotope of radium, or (b) if the energy component considered originates as X- or γ-radiation. The relative damage factor is taken as 5 in all other cases, i.e. if the parent element of the chain is not an isotope of radium and if the energy component considered originates as α-, β^--, β^+-, e^-- radiation or from a recoil atom. Thus, the first two elements in the Th^{228} chain are $Th^{228} \xrightarrow{\alpha,\gamma} Ra^{224} \xrightarrow{\alpha,\gamma}$ and the value of n is 5 for the energies of both these α-particles. In the chain $Ra^{228} \xrightarrow{\beta} Ac^{228} \xrightarrow{\beta,\gamma} Th^{228} \xrightarrow{\alpha,\gamma} Ra^{224} \xrightarrow{\alpha,\gamma}$ the same two α-energies are weighted with $n = 1$. The γ-energy is always weighted with $n = 1$.

When the necessary data are available, the maximum permissible body burden, q, of a radionuclide may be determined by a comparative study of the clinical findings and biological damage produced by various quantities of Ra^{226} and the radionuclide under study. Studies of chronic exposure[17]—a few of which have been started—should furnish the most direct and reliable values of q. Until these studies have been completed, it will be necessary to continue to determine values of q by a direct comparison of the energy deposited in bone by the particular radionuclide with the energy deposited by 0.1 μc of Ra^{226} and its daughter products (with an RBE of 10), modified by the factor, n. In this case, the value of q is given by the equation

$$q = \frac{q^{Ra} f_2^{Ra}}{f_2} \times \frac{\varepsilon^{Ra}}{\varepsilon} = \frac{0.1\ (0.99)}{f_2} \times \frac{110}{\varepsilon} = \frac{11}{f_2 \varepsilon} \tag{1}$$

in which

$q^{Ra} = 0.1\ \mu c$ is the maximum permissible body burden of Ra^{226};

f_2 = fraction of radionuclide in the skeleton of that in the total body;

$f_2^{Ra} = 0.99$ is the value of f_2 for radium;

ε = effective absorbed energy per disintegration of a radionuclide = $\Sigma EF(\mathrm{RBE})n$; $\varepsilon^{Ra} = 110$ is the value of ε for radium;

E = energy (MeV) deposited in skeleton per disintegration;

RBE = relative biological effectiveness = 1 for X, γ, β^-, β^+, e^-, (it is set equal to 1.7 if the maximum energy, $E_m \leqslant 0.03$ MeV for β^-, β^+ or e^-), 10 for α and 20 for recoil atoms;

F = ratio of disintegrations of daughter to disintegrations of parent. See Section V.1.

It is assumed that 99 per cent of the radium in the body is in the skeleton, and the total energy deposited in the skeleton per disintegration of Ra^{226} plus 30 per cent of its daughter products[18, 19] is 11 MeV, and thus the effective energy deposited in the skeleton is $\Sigma EF(\mathrm{RBE})n = 110$*. For other radionuclides which are localized in the bone, the effective absorbed energy is found from $\Sigma EF(\mathrm{RBE})n$.

Thus, 0.1 μc of Ra^{226} and its daughter products in the body corresponds to an average absorbed dose rate to the bone of 0.06 rad/week or an average dose rate to the bone of 0.56 rem/week. As indicated above, the factor, n, was set equal to 1 in arriving at these dose rates for Ra^{226}. The distribution of radium in bone is not uniform,[14] and, for example, if there are portions of the bone in which radium is concentrated, the dose rate in these areas might be many times the average values. These values of RBE dose rate are based on the assumption that $(\mathrm{RBE})_\alpha = 10$. Many experiments[20] indicate that $(\mathrm{RBE})_\alpha$ is much smaller than 10 for biological damage resulting from acute exposure—perhaps as small as 1.4—but for biological damage from chronic exposures much higher applicable values have been reported.[21] Therefore, until more data from chronic exposures are available it would be unwise to use a value of $(\mathrm{RBE})_\alpha < 10$. Occupational and medical experience with radium offers much more justification for accepting the 0.1 μc of Ra^{226} and for the RBE dose

* This value was given as 162 MeV in the 1955 ICRP report[3] but is changed to 110 MeV in this 1958 edition. The reduction to 110 MeV is the result of using the more recent data of Norris[18] which indicate a bone retention of 30 per cent of the daughter products of Ra^{226}. The earlier data of Evans [19] which assumed 55 per cent retention of the daughter products of Ra^{226} had been used to obtain the 162 MeV. Details of calculation of this effective absorbed energy are given in Section V.1.

of Ra^{226} is not reached except following continuous occupational exposure at the MPC values. For the more dangerous bone-seeking radionuclides, this requires continuous occupational exposure for 50 years at the MPC level.

3. Body burden based on a permissible RBE dose rate to the critical body organ. Because specific experimental information is lacking for assessing values of safe body burdens of the radionuclides that are not localized in the bone, the MPC and q values were calculated on the premise that a maximum permissible body burden is that amount distributed throughout the body that will result in a maximum permissible RBE dose rate to the critical organ. The maximum RBE dose rates permitted to the various body organs are listed in Section II.2. It should be emphasized that these maximum permissible RBE dose rates are values averaged during a quarter. Variations of these rates over shorter intervals may be expected and are permissible. As explained in Section II, the average dose rate of 0.1 rem/week and corresponding MPC values for occupational exposure of the gonads or total body may be increased over a 13 week period by a factor as large as 2.4, provided the dose at any age N does not exceed that given by the formula $5(N-18)$ and provided adequate monitoring is used to insure that the dose in a 13 week period does not exceed 3 rems.

In the following discussion, the distribution of the isotope in the body is characterized by the following parameters:

f_1 = the fraction of ingested radionuclides reaching the blood;
f_2' = the fraction of the nuclide in the blood that reaches the organ of reference;
$f_w = f_1 f_2'$, see Section V.3;
f_a = the fraction of inhaled radionuclide reaching the organ of reference, see Section V.3;
f_2 = the fraction of the body burden in the organ of reference, see Section V.3.

The equation for maximum permissible body burden, q, based on a maximum permissible dose rate R rem/week is

$$q = \frac{100\, mR}{3.7 \times 10^4 \times 1.6 \times 10^{-6} \times 6.05 \times 10^5 f_2 \varepsilon} \tag{2}$$

$$q = \frac{2.8 \times 10^{-3}\, m\, R}{f_2\, \varepsilon} \tag{3}$$

and when $R = 0.3$ rem/week

$$q = \frac{8.4 \times 10^{-4}\, m}{f_2 \varepsilon} \tag{4}$$

where 3.700×10^4 = dis/sec per μc;
1.6×10^{-6} = ergs/MeV;
6.05×10^5 = sec/week;
100 = ergs/g per rad;
m = mass of the organ of reference (g);
and ε is defined as for equation (1).

it delivers to the bone as a basic reference for permissible occupational exposure than any arbitrarily chosen dose rate to individual organs. At this time, it would be difficult to say which is more harmful to man, (a) the dose rate to the total body of 0.1 rem/week, or (b) the dose rate to the bone resulting from a body burden of 0.1 μc of Ra^{226}. Certainly, if a major portion of the hematopoietic system were irradiated, e.g. concurrently from the spleen-seeking Po^{210} and from the bone-seeking Ra^{226}, the biological damage would be greater than if only a part of it were irradiated. It has been shown[8] that in some cases a synergistic effect results when several organs of the body are irradiated simultaneously. Thus, it is rather certain that 0.1 rem/week to the bone is less harmful than 0.1 rem/week to the total body but, at present, sufficient quantitative data are lacking to indicate whether or not an average dose rate of 0.56 rem/week (involving, perhaps, a much higher local dose rate) to the bone produces greater or less damage than 0.1 rem/week to the entire body.

The development of bone tumors many years after exposure (from 10 to 35 years) has been the principal hazard to patients given large medical doses of radium and to the radium dial painters. Although tumors have not been observed in persons with body burdens of radium as low as 0.1 μc, the factor of safety may not be as large as 10 because tumors have occurred in persons having a body burden less than 1μc of radium at the time the tumor was first detected. However, in all these cases the original body burden had been greater than it was when the tumor was first detected. Furthermore, in most cases the integrated absorbed dose received by the radium dial painters had been much enhanced because a large amount of mesothorium (Ra^{228}) was in the ingested material. There is an additional factor of safety in the MPC values for the long-lived radionuclides in Table 1 in that the maximum permissible body burden is reached only after an extended exposure at the MPC level (see Section III.1). For the radionuclides (Table 2) with a long effective half-life, e.g. Ra^{226}, Th^{230}, Th^{232}, Np^{237}, Pu^{239}, Am^{243}, Cm^{246}, etc., the maximum permissible body burden is not reached until after 50 years of continuous occupational exposure. Several workers[22] have described changes in skeletal density and/or histopathological changes in the bone of patients who have 0.1 μc or less of radium, and more pathological changes may be expected as these individuals become older. This problem will be kept constantly under advisement, and as more data are accumulated on the chronic effects of radium and other bone-seeking radionuclides, it may be desirable at a later date to lower the basic reference of 0.1 μc of Ra^{226}. However, at the present time, this change does not seem to be warranted for reasons as follows: (a) radium does not irradiate the entire hematopoietic system; (b) body burdens of 0.1 μc of Ra^{226} probably produce detectable changes in the bone but are not known to have caused serious damage (demonstrable harm to the individual); (c) the principal recognizable damage from Ra^{226} is the production of bone tumors, but the lowest body burden that has resulted in a tumor is 0.5 μc;[23] (d) all radium-produced tumors have occurred in persons whose original body burdens had been much greater than at the time the tumors were discovered; (e) most bone tumors arising in radium dial painters may be attributed to Ra^{226} + Ra^{228} in which the integrated RBE dose was much greater than would be indicated by the Ra^{226} burden at the time the tumors were discovered; and (f) the maximum permissible body burden of a bone-seeking radionuclide corresponding to 0.1 μc

4. Concentrations in air and water—based on exponential model—critical organs other than gastrointestinal (GI) tract. Maximum permissible concentrations in air and in water in Table 1 were calculated for most of the radionuclides on the assumption that the radioactive material is taken into the critical body organ at the rate of P μc/day and that the biological elimination from the critical organ follows a simple exponential law. This relationship is expressed by the equation;

$$\frac{d(qf_2)}{dt} + \lambda(qf_2) = P \tag{5}$$

The solution with $qf_2 = 0$ when $t = 0$ is

$$qf_2 = P(1 - e^{-\lambda t})/\lambda \tag{6}$$

in which qf_2 = burden of the radionuclide in the critical body organ (μc);

f_2 = fraction of radionuclide in critical organ of that in total body;
λ = effective decay constant = $0.693/T$;
T = effective half-life $(T_r T_b)/(T_r + T_b)$ (days);
T_r = radioactive half-life (days);
T_b = biological half-life (days);
t = period of exposure; for occupational exposure $t = 50$ years (in the previous publications of NCRP[1] and ICRP[2] t was set to equal 70 years);
P = rate of uptake of the radionuclide by the critical body organ (μc/day) = $(M)S$, where M is the concentration (μc/cm^3) of the radionuclide in water or in air taken into the body, and S is the product of the average rate of intake (cm^3/day) of water or of air and the fraction of the microcuries arriving in the critical body organ. For occupational exposure at the maximum permissible concentration (MPC) of the radionuclide in water, $M = (\text{MPC})_w$ and in air, $M = (\text{MPC})_a$. In a 24 hr day, the standard man (see Section V.2 for a discussion of the standard man) consumes 2200 cm^3 of water and breathes 2×10^7 cm^3 of air. Because of his greater activity during an 8 hr work day, it is assumed that half of this body intake occurs during the work period, viz. 1100 cm^3 of water and 10^7 cm^3 of air. The work schedule for the standard man is 8 hr/day, 5 days/week and 50 weeks/year. Therefore for the average occupational exposure, $S = 1100 \times 5/7 \times 50/52 f_w = 750\ f_w$ cm^3 of water per day and $S = 10^7 \times 5/7 \times 50/52 f_a = 6.9 \times 10^6 f_a$ cm^3 of air per day.

The formulas that follow in this section are all based on a 40 hr/week exposure period whenever specific time data are involved. For continuous occupational exposure the MPC values should be divided by $2 \times 365/(5 \times 50) = 2.92$ except

for submersion where they should be divided by $3 \times 365/(5 \times 50) = 4.38$. Substituting the above values for P and λ in equation (6) the MPC values are determined by

$$(\mathrm{MPC})_a = \frac{10^{-7}\, q f_2}{T f_a\,(1 - e^{-0.693\, t/T})}\ \mu\mathrm{c/cm^3} \tag{7}$$

and

$$(\mathrm{MPC})_w = \frac{9.2 \times 10^{-4}\, q f_2}{T f_w\,(1 - e^{-0.693\, t/T})}\ \mu\mathrm{c/cm^3} \tag{8}$$

T = effective half-life (days);
t = period of exposure (days).

If the radionuclide disintegrates into one or more daughter radionuclides, proper account must be taken of the contribution to the RBE dose by the daughter radionuclides that are produced in the body. Formulas (7) and (8) may be modified so that they remain correct for a chain of parent–daughter radionuclides. This can be done by simply augmenting the effective energy of the parent by the effective energy of each daughter weighted by the frequency of the daughter disintegrations per disintegration of parent. This ratio defines the factor F_i, i.e.

$$F_i = \frac{\mu\mathrm{c\ of\ } i\mathrm{th\ daughter\ in\ the\ organ}}{\mu\mathrm{c\ of\ parent\ in\ the\ organ}}$$

Thus in the case[24] of a single intake, if P μc of the parent radionuclide reaches the critical organ at time $t = 0$, the organ burden $(qf_2)_i^s$ of the ith daughter product at time t is given by the equation

$$(qf_2)_0^s = P\, e^{-\lambda_0 t}$$

$$(qf_2)_1^s = P\, \lambda_1^r \left[\frac{e^{-\lambda_0 t}}{\lambda_1 - \lambda_0} + \frac{e^{-\lambda_1 t}}{\lambda_0 - \lambda_1}\right]$$

$$(qf_2)_2^s = P\, \lambda_1^r \lambda_2^r \left[\frac{e^{-\lambda_0 t}}{(\lambda_1 - \lambda_0)(\lambda_2 - \lambda_0)} + \frac{e^{-\lambda_1 t}}{(\lambda_0 - \lambda_1)(\lambda_2 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_0 - \lambda_2)(\lambda_1 - \lambda_2)}\right]$$

The general formula is

$$(qf_2)_i^s = P\left[\prod_{j=1}^{i} \lambda_j^r\right] \sum_{h=0}^{i} \frac{e^{-\lambda_h t}}{\prod\limits_{\substack{p=0 \\ p \neq h}}^{i} (\lambda_p - \lambda_h)} \tag{9}$$

In this formula $\left[\prod_{j=1}^{i} \lambda_j^r\right]$ denotes the product $\lambda_1^r \times \lambda_2^r \times \ldots \times \lambda_i^r$.

If it is understood that when $i = 0$ the empty product $\left[\prod_{j=1}^{0} \lambda_j^r\right]$ is equal to 1, this general formula (9) is applicable to the total body burden of the parent as well as the daughter radionuclides. In the following discussion, the subscript, 0, as in $\lambda_0^r = 0.693/T_0^r$, etc., always refers to the parent isotope while the subscript i indicates the decay constants of the ith daughter.

When there is continuous intake of the parent radionuclide so that P μc/day of the parent radionuclide reaches the critical organ, the organ burden $(qf_2)_i$ of the ith daughter product at time t is given by the equation:

$$(qf_2)_0 = P(1 - e^{-\lambda_0 t})/\lambda_0$$

$$(qf_2)_1 = P\,\lambda_1^r \left[\frac{(1 - e^{-\lambda_0 t})}{\lambda_0(\lambda_1 - \lambda_0)} + \frac{(1 - e^{-\lambda_1 t})}{\lambda_1(\lambda_0 - \lambda_1)}\right]$$

$$(qf_2)_2 = P\,\lambda_1^r\lambda_2^r\left[\frac{(1 - e^{-\lambda_0 t})}{\lambda_0(\lambda_1 - \lambda_0)\,(\lambda_2 - \lambda_0)} + \frac{(1 - e^{-\lambda_1 t})}{\lambda_1(\lambda_0 - \lambda_1)\,(\lambda_2 - \lambda_1)} + \frac{(1 - e^{-\lambda_2 t})}{\lambda_2(\lambda_0 - \lambda_2)\,(\lambda_1 - \lambda_2)}\right]$$

The general formula is

$$(qf_2)_i^s = \int_0^t (qf_2)_i^s\,dt = P\left[\prod_{j=1}^{i} \lambda_j^r\right]\sum_{j=0}^{i} \frac{1 - e^{-\lambda_h t}}{\lambda_h \prod\limits_{\substack{p=0\\ p\neq h}}^{i} (\lambda_p - \lambda_h)} \tag{10}$$

It is to be noted that equation (10) includes equation (6) as a special case if it is understood that when $i = 0$ the empty product is replaced by 1. The dose rate in rems/week to the critical body organ resulting from the continuous body intake and deposition of the parent radionuclide and from the growth of the daughter radionuclides in the critical body organ is given by the equation:

$$R = \sum_{i=0}^{k} (qf_2)_i \frac{3.7\times10^4\times24\times3600\times7\times1.6\times10^{-6}\,E_i\,(\mathrm{RBE})_i n_i}{100\,m}\ \text{rems/week} \tag{11}$$

in which m is the mass of the critical organ, and $E_i\,(\mathrm{RBE})_i n_i$ is the effective energy corresponding to one disintegration of an ith daughter atom. The factor P is taken as $6.9 \times 10^6 \times (\mathrm{MPC})_a f_a$ for inhalation and as $750\ (\mathrm{MPC})_w f_w$ for ingestion, and since the factor P occurs in each of the (qf_2) terms in equation (11), and since $(qf_2)_0 = P(1 - e^{-\lambda_0 t})/\lambda_0$

$$(\mathrm{MPC})_a = \frac{4.1\times10^{-10}\,m\,R}{f_a \sum\limits_{i=0}^{k} (qf_2)_i\,E_i\,(\mathrm{RBE})_i n_i/P}\ \mu\mathrm{c/cm^3} = \frac{4.1\times10^{-10}\,m\,R\,\lambda_0}{f_a(1-e^{-\lambda_0 t})\sum\limits_{i=0}^{k} E_i F_i (\mathrm{RBE})_i n_i}\ \mu\mathrm{c/cm^3} \tag{12}$$

$$(\mathrm{MPC})_w = \frac{3.7\times10^{-6}\,mR}{f_w \sum_{i=0}^{k} (qf_2)_i E_i (\mathrm{RBE})_i n_i/P}\ \mu\mathrm{c/cm^3} = \frac{3.7\times10^{-6}\,m\,R\,\lambda_0}{f_w(1-e^{-\lambda_0 t}) \sum_{i=0}^{k} E_i F_i (\mathrm{RBE})_i n_i}\ \mu\mathrm{c/cm^3} \quad (13)$$

with $F_0 = 1$ and $F_i = (qf_2)_i/(qf_2)_0$. In equations (12) and (13) R is the permissible dose rate to the organ in rems/week. Thus if particulate radiation is involved $R=0.56$ when bone is the critical organ and $R = 0.3$ for all other organs except thyroid and skin, in which cases $R = 0.6$ or for total body and gonads where $R = 0.1$. The weighted sum of chain energies $\Sigma E_i F_i\ (\mathrm{RBE})_i n_i$ and the fractions F_i are listed in Table 5(a). In all organs other than bone n_i is taken as 1. Equations (12) and (13) are based on the 40 hr week. The corresponding formulas for the 168 hr week, i.e. continuous exposure, are obtained by replacing the constants 4.1×10^{-10} and 3.7×10^{-6} by 1.4×10^{-10} and 1.3×10^{-6}, respectively.

5. Concentrations in air and water based on RBE dose delivered to various segments of the GI tract. When the critical organ considered is the gastrointestinal (GI) tract, the amount (μc) of the ith daughter present at time t is given by formulas similar to equation (9), but since the material moves along the intestines at somewhat different rates, formula (11) also needs adjustment. If τ is the total time spent in a section of the GI tract, e.g. the upper large intestine, then during a time interval $d\tau$ the fraction of the total contents which moves by a given site is, on the average, $d\tau/\tau$. The mass of this material is thus $d\tau/\tau \times m$, where m is the total mass of the contents of the section being considered. The energy is, to a first approximation, absorbed in this mass. Thus if there is continuous intake of P μc/day, then the dose rate in rems/week to the walls of the GI tract near the site is given by

$$R = \sum_{i=0}^{k} (qf_2)_i^{\ \mathrm{total}} \frac{3.7 \times 10^4 \times 24 \times 3600 \times 7 \times 1.6 \times 10^{-6} \varepsilon_i\, d\tau}{2 \times 100\, m \times d\tau/\tau}\ \text{rems/week} \quad (14)$$

In the case of an isotope with no daughters, the value of $(\mathrm{MPC})_a$ is

$$(\mathrm{MPC})_a = \frac{8.2 \times 10^{-10}\, m\, R}{f_a \tau \varepsilon_0 e^{-\lambda_0 t}}\ \mu\mathrm{c/cm^3} \quad (15)$$

and the value of $(\mathrm{MPC})_w$ is

$$(\mathrm{MPC})_w = \frac{7.4 \times 10^{-6}\, m\, R}{\tau \varepsilon_0 e^{-\lambda_0 t}}\ \mu\mathrm{c/cm^3} \quad (16)$$

If the radionuclide considered is the parent of a chain of k daughters, the corresponding formula for $(\mathrm{MPC})_a$ is

$$(\mathrm{MPC})_a = \frac{8.2 \times 10^{-10}\, m\, R}{\tau f_a \sum_{i=0}^{k} \frac{(qf_2)_i^{\ \mathrm{total}}}{P} \varepsilon_i}\ \mu\mathrm{c/cm^3} \quad (15')$$

and the value of $(\mathrm{MPC})_w$ is

$$(\mathrm{MPC})_w = \frac{7.4 \times 10^{-6}\, m\, R}{\tau \sum_{i=0}^{k} \frac{(q f_2)_i^{\mathrm{total}}}{P}\, \varepsilon_i} \ \mu\mathrm{c/cm^3} \tag{16'}$$

The values of the biological constants used for the different sections of the GI tract are listed in Table 11. Since daughter elements also enter the small intestine and the large intestine, each subdaughter is the parent for a subchain and $(q f_2)_i^s$ must be computed by equation (9) for all such subchains and the results added to give the amount of ith daughter in the organ. This will be denoted by $(q f_2)_i^{\mathrm{total}}$. A factor of $\frac{1}{2}$ has been included in formulas (14) through (19′) to take account of the fact that the dose to the intestinal wall is, on the average, only half the dose to the contents of the GI tract. In equations (15′) and (16′) $(q f_2)_i^{\mathrm{total}}$ represents the amount of the ith isotope (μc) (equation (9)), and the formulas were computed in this form. Thus the factors F_i are not needed and since the relative damage factor $n_i = 1$ for the GI tract, the effective energy reduces to $\varepsilon_i = \Sigma E$ (RBE) which is tabulated in Tables 5 and 5(a). Experiments[25] have shown that α-particles fail to penetrate the mucosa to an appreciable extent. Therefore, the Committee has decided to include only 1 per cent of the energy of the α-particles in computing the effective energies, $\Sigma\varepsilon_i$, for the GI tract. In calculating $(q f_2)_i^{\mathrm{total}}$ it is assumed that there is no absorption of the material from the large intestine, and thus $\lambda_i^b = 0$ and $\lambda_i = \lambda_i^r$ in these sections of the tract. The same is assumed for the stomach. In the small intestine a fraction f_1 is absorbed and a value of λ_i^b is chosen so that absorption at this constant rate during the time of passage amounts to a total absorption of a fraction f_1 of the material. Equations (15) and (16) are applied when the critical portion of the GI tract is the small intestine, SI, upper large intestine, ULI, or the lower large intestine, LLI. Since the upper large intestine and the lower large intestine have the same diameter, the effective energy is the same for these two sections. This common value is listed in Tables 5 and 5(a) as the value for the large intestine, LI. The calculations for the stomach, S, are somewhat different since it is assumed that the ingested material remains in the stomach for 1 hr. Thus, the dose to the stomach is given by

$$R = \sum_{i=0}^{k} \int_0^{1/24} \frac{(q f_2)_i^s \times 3.7 \times 10^4 \times 24 \times 3600 \times 7 \times 1.6 \times 10^{-6}\, \varepsilon_i\, d\tau}{2 \times 100\, m} \ \mathrm{rems/week} \tag{17}$$

In the case of an isotope with no daughters the value of $(\mathrm{MPC})_a$ is

$$(\mathrm{MPC})_a = \frac{2.5 \times 10^{-10}\, m\, \lambda_0}{f_a\, \varepsilon_0\, (1 - e^{-\lambda_0/24})} \ \mu\mathrm{c/cm^3} \tag{18}$$

and the value of $(\mathrm{MPC})_w$ in this case is

$$(\mathrm{MPC})_w = \frac{2.2 \times 10^{-6}\, m\, \lambda_0}{\varepsilon_0\, (1 - e^{-\lambda_0/24})} \ \mu\mathrm{c/cm^3} \tag{19}$$

If the radionuclide considered is the parent of a chain of k daughters and the stomach is the critical tissue, the corresponding formula for $(\mathrm{MPC})_a$ is

$$(\mathrm{MPC})_a = \frac{2.5 \times 10^{-10}\, m}{f_a \sum_{i=0}^{k} \varepsilon_i \left[\prod_{j=1}^{i} \lambda_j^r\right] \sum_{h=0}^{i} \frac{(1 - e^{-\lambda_h/24})}{\lambda_h \prod_{\substack{p=0 \\ p \neq h}}^{i} (\lambda_p - \lambda_h)}} \ \mu\mathrm{c/cm^3} \tag{18'}$$

and the value of $(\mathrm{MPC})_w$ when the stomach is the critical tissue is

$$(\mathrm{MPC})_w = \frac{2.2 \times 10^{-6}\, m}{\sum_{i=0}^{k} \varepsilon_i \left[\prod_{j=1}^{i} \lambda_j^r\right] \sum_{h=0}^{i} \frac{(1 - e^{-\lambda_h/24})}{\lambda_h \prod_{\substack{p=0 \\ p \neq h}}^{i} (\lambda_p - \lambda_h)}} \ \mu\mathrm{c/cm^3} \tag{19'}$$

The notation in formulas (18) through (19′) is chosen in agreement with the notation of formula (10) on which these are based. However, as explained above, no absorption occurs in the stomach so that $\lambda_i^b = 0$ and thus λ_i in formulas (18) through (19′) is equal to λ_i^r, i.e. $\lambda_i = \lambda_i^r + \lambda_i^b = \lambda_i^r + 0 = \lambda_i^r$. For some isotopes the dose rate to the intestinal wall passes through a maximum value during the time of passage through the GI tract, and thus it is necessary to determine this maximum and equate it to 0.3 rem/week in determining the maximum permissible intake. The use of the single intake formulas for $(qf_2)_i^s$ and $(qf_2)_i^{\text{total}}$ in equations (14) through (19′) instead of continuous intake formulas for the organ burden as in equations (10) through (13) follows from the fact that by our assumption of continuous movement at a uniform rate through each section of the tract the isotope never accumulates in the GI tract, and thus the dose at a position reached at time t after ingestion of material is entirely independent of what material was ingested before time $t = 0$ or following time $t = 0$. This is, of course, an oversimplification since there is some irradiation of one portion of the GI tract by any γ-radiation in the body and, perhaps, by some β-rays emitted in other portions of the tract. To a large extent this is taken into account in computing the effective energies, ε_i, which are calculated for each section of the tract as a whole and not merely for a very small portion of the tract.

6. Maximum permissible concentration of radionuclides of noble gases and other relatively inert gases. In dealing with inert gases, such as A^{41} and Xe^{135}, the calculations are not based on the dose delivered by the concentration of the radioactive material inside the body, but rather on the dose the person would receive if he were surrounded by a semispherical infinite cloud of radioactive gas. In this case, one would expect the radiation from the radioactive cloud to deliver a much higher dose than that from the gas held in the lungs or other body organs. It follows that the body is assumed to be irradiated from half the solid angle by this radioactive cloud of large volume.

The maximum permissible concentration of an inert gas under these conditions is,

$$(\mathrm{MPC})'_a = \frac{0.024\,R}{\Sigma\,(E)}\,\rho_a\,P_a/P_t\ \mu\mathrm{c/cm^3} \tag{20}$$

When the maximum permissible dose rate R is 0.1 rem/week,

$$(\mathrm{MPC})'_a = \frac{2.6 \times 10^{-6}}{\Sigma\,(E)}\ \mu\mathrm{c/cm^3} \tag{21}$$

in which ρ_a = density of air (= 0.0012 g/cm³);

P_a/P_t = stopping power of air relative to tissue; $P_a/P_t = 1/1.13$ for β and secondary electrons produced by X- and γ-radiation;

$\Sigma\,(E)$ = effective energy per disintegration (MeV); in this case RBE = 1 and $n = 1$;

$(\mathrm{MPC})'_a$ = maximum permissible concentration (μc/cm³) in a large cloud of gas that will deliver a dose at the rate of 0.1 rem/week.*

Equation (21) is applied only in the case of large clouds of noble gases or other relatively inert gases that emit γ or high energy β-radiation ($E_m \geqslant 0.1$ MeV). This equation is applicable to occupational exposure (i.e. 40 hr/week) and for the case where a person is surrounded by an infinite semispherical cloud of radioactive material that emits γ-, X- or β-radiation of sufficient energy to constitute essentially a total body exposure and necessitate limiting the dose rate to 0.1 rem/week.

The above formula was not used for noble gases that are principally α-emitters, e.g. Rn^{222} and Rn^{220}, or for other relatively inert gases that emit low energy ($\leqslant 0.1$ MeV) β-radiation, e.g. H^3_2, because the radiation would not penetrate the protective epidermal layer of skin surrounding the body. In the case of such low energy radiation formula (20) still applies but with $R = 0.6$ rem/week. Such cases are listed in Table 1 with "submersion skin" as the organ of reference. Experiments have shown that when HTO vapor is present in air approximately equal amounts enter the body by inhalation and absorption through the skin. Thus the value computed by equation (7) must be halved in this case.

In 1941 the United States Advisory Committee on X-ray and Radium Protection[12] set 10^{-8} μc/cm³ as the value of $(\mathrm{MPC})_a$ for occupational exposure (40 hr week) to Rn^{222} plus its daughter products. However, the ICRP[2] gave an $(\mathrm{MPC})_a$ value of 10^{-7} μc/cm³ for continuous exposure (168 hr/week). Despite the wide disparity of these values and the long record of experience with radon, there are few, if any, well-established cases of serious damage from exposures at these levels. Nevertheless, calculations indicate that an air concentration of 10^{-7} μc/cm³ might lead to an excessively large dose to the bronchi, and the NCRP[1] previously had recommended the value of 10^{-8} μc/cm³ as $(\mathrm{MPC})_a$ for Rn^{222} plus daughters (168 hr/week).

* In the previous publication of this report,[2] the exposure rate was taken as 0.3 rem/week rather than 0.1 rem/week, and the radioactive cloud was assumed to comprise an infinite sphere rather than an infinite semisphere about the body. Also, the equations were given for continuous exposure rather than for the typical week of work. Therefore, previously published MPC values have been increased by three factors, viz. $1/3 \times 2 \times 4.4 = 2.9$. The new assumptions are thought to be sufficiently conservative in all practical cases.

Recent studies[26] have indicated that when radon and its daughters are present in ordinary air the free ions of RaA constitute only about 10 per cent of the total number of RaA atoms that would be present at equilibrium and these unattached atoms deliver all but a small fraction of the dose to the bronchi. Based on these measured dose rates the $(MPC)_a$ for exposure to radon and daughter products is found to be $3 \times 10^{-6}/(1 + 1000f)$ where f is the fraction of the equilibrium amount of RaA ions which are unattached to nuclei.

For Rn^{220} the major portion of the dose to the bronchi is due to free ions of ThB which reach only 1/2000 of the equilibrium number in ordinary unfiltered air. Because of this and energy considerations the $(MPC)_a$ value will be higher and is recommended as $6 \times 10^{-6}/(1 + 40000f)$ if the free ions of ThB constitute a fraction f of the equilibrium number of such atoms. The values given here for radon and daughters and for thoron and daughters are for the 40 hr week.

7. Maximum permissible concentration of unidentified radionuclides (MPCU). The identity of the radioactive contaminants in air, water and food must be established before appropriate MPC values can be applied either for occupational exposure or for exposure to population outside of controlled areas. In many cases there is no question regarding the identity of a radionuclide because the operation involves only one radionuclide. Sometimes, however, preliminary surveys reveal the presence of radioactive contamination, and considerable uncertainty exists as to which radionuclides are the major contributors. When a laboratory is using a number of radionuclides, e.g. mixed fission products, an air sample may furnish only a few clues as to the identity of the radionuclide. By using the simplest of equipment and techniques, the level of air contamination may be established in a matter of minutes, but hours or even days may be required to conduct the radiochemical analyses necessary to identify the one or more radionuclides that are present in the air. Fortunately, in such cases it usually is not necessary to go through a tedious, time consuming and expensive radiochemical analysis. If it is determined that certain of the more dangerous radionuclides are not present, i.e. the concentration of the more dangerous is small compared with the MPC values in Table 1, the operation may be continued safely regardless of the radionuclide or mixture of radionuclides, provided the concentration does not exceed the values for MPC of unidentified (MPCU) radionuclides as listed in Table 3 for water or in Table 4 for air. These MPCU values are applicable to continuous occupational exposure (168 hr/week), and should be multiplied by one-tenth if they are to be applied as interim values outside of and in the neighborhood of the controlled exposure area. It should be pointed out that the use of MPCU values may save an immense amount of effort and expense if they are applied properly to avoid unnecessary radionuclide analyses in areas where the air, water and food contamination is usually less than the appropriate MPCU values. On the other hand, they can impose a needless penalty if improperly applied. For example, if initial measurements indicate a negligible amount of Ra^{226} and Ra^{228} in the drinking water of a small community near an atomic energy laboratory, and if it is determined by daily gross α-, β- and γ-sample counting that the activity does not exceed the MPCU value ($\frac{1}{10} \times 1 \times 10^{-6}\ \mu c/cm^3 = 1 \times 10^{-7}\ \mu c/cm^3$) it would seem foolish to carry out a daily radiochemical analysis of this water. If, on the other hand,

course, the criteria for these organs must also be considered, and the application of equation (23) will prevent any particular organ from exceeding the permissible limit set for that organ. However, it would seem too conservative and contrary to the intent of the basic rules to limit the dose to any portion of the body to a maximum rate of 0.1 rem/week merely because the entire body is receiving some dose, though it may be very small in most of the body and only be at the rate of 0.1 rem/week in a small portion. The values of $(\mathrm{MPC})^{T.B.}$ as given in Table 1 and as applied in equation (24) were derived on the assumption that the total body dose of interest in this case is the gram-rem dose or the total weighted energy delivered to the total body. On this basis the total body burden was obtained from equation (3) by setting m equal to the mass of the total body ($m = 70{,}000$ g), $f_2 = 1$, ε equal to the weighted absorbed energy, $n = 1$ and $R = 0.1$ rem/week.

The application of these criteria may be illustrated by the following example: Suppose the mixture consists of Sr^{90}, Pu^{239} and Na^{24}, and that an external γ-source is also present, and that the measured intensities are those indicated in Table *A*.

Table A. Calculation of MPC of a mixture of radionuclides

Example of Concurrent Exposure to Several Radionuclides (in Soluble Form) Present in Air and Water and to an External Source of Radiation

Source of exposure	Body organ exposed	In air*	In water*
Sr^{90}	Bone	$\frac{\rho_{aA}}{(\mathrm{MPC})^{x}_{aA}} = \frac{1.8\times10^{-11}\ \mu c/cm^3}{3\times10^{-10}\ \mu c/cm^3}$	$\frac{\rho_{wA}}{(\mathrm{MPC})^{x}_{wA}} = \frac{1.5\times10^{-7}\ \mu c/cm^3}{4\times10^{-6}\ \mu c/cm^3}$
	Total body	$\frac{\rho_{aA}}{(\mathrm{MPC})^{T.B.}_{aA}} = \frac{1.8\times10^{-11}\ \mu c/cm^3}{9\times10^{-10}\ \mu c/cm^3}$	$\frac{\rho_{wA}}{(\mathrm{MPC})^{T.B.}_{wA}} = \frac{1.5\times10^{-7}\ \mu c/cm^3}{1\times10^{-5}\ \mu c/cm^3}$
Pu^{239}	Bone	$\frac{\rho_{aB}}{(\mathrm{MPC})^{x}_{aB}} = \frac{4\times10^{-13}\ \mu c/cm^3}{2\times10^{-12}\ \mu c/cm^3}$	$\frac{\rho_{wB}}{(\mathrm{MPC})^{x}_{wB}} = \frac{1.3\times10^{-5}\ \mu c/cm^3}{1\times10^{-4}\ \mu c/cm^3}$
	Total body	$\frac{\rho_{aB}}{(\mathrm{MPC})^{T.B.}_{aB}} = \frac{4\times10^{-13}\ \mu c/cm^3}{1\times10^{-11}\ \mu c/cm^3}$	$\frac{\rho_{wB}}{(\mathrm{MPC})^{T.B.}_{wB}} = \frac{1.3\times10^{-5}\ \mu c/cm^3}{1\times10^{-3}\ \mu c/cm^3}$
Na^{24}	Total body	$\frac{\rho_{aC}}{(\mathrm{MPC})^{T.B.}_{aC}} = \frac{2\times10^{-7}\ \mu c/cm^3}{2\times10^{-6}\ \mu c/cm^3}$	$\frac{\rho_{wC}}{(\mathrm{MPC})^{T.B.}_{wC}} = \frac{2\times10^{-3}\ \mu c/cm^3}{1\times10^{-2}\ \mu c/cm^3}$
γ †		Bone $\frac{R^{x}_{\gamma}}{L^{x}} = \frac{0.065\ \text{rem/week}}{0.56\ \text{rem/week}}$	
		Total body $\frac{R^{T.B.}_{\gamma}}{L^{T.B.}} = \frac{0.065\ \text{rem/week}}{0.1\ \text{rem/week}}$	

* The ratios given for Sr^{90}, Pu^{239} and Na^{24} are the ($\mu c/cm^3$ present in air)/$(\mathrm{MPC})^{x}_{aA}$ where $(\mathrm{MPC})^{x}_{aA}$ is the $(\mathrm{MPC})_a$ for element A (Sr^{90}) and organ x (bone), etc.

† The ratio given for γ is the (actual RBE dose rate)/(maximum permissible RBE dose rate).

the level ranged between 10^{-5} and 2×10^{-5} $\mu c/cm^3$, it would be unwise to shut down the plant or to instigate an expensive modification of the operation without first identifying the radionuclides, for it might be that the contamination in the water is from Na^{24} and P^{32}. In this case, the appropriate MPC value for application in the neighborhood of the plant is $\frac{1}{10} \times 2 \times 10^{-3} = 2 \times 10^{-4}$ and $\frac{1}{10} \times 2 \times 10^{-4} = 2 \times 10^{-5}$, respectively (see Table 1).

8. Maximum permissible concentration of known mixtures of radionuclides. Suppose a person is exposed to concentrations $\rho_{aA}, \rho_{aB}, \ldots \rho_{wA}, \rho_{wB} \ldots$ $\mu c/cm^3$ of isotopes $A, B, \ldots$ in air and in water, respectively, and also to external sources of γ and neutron radiations. Assume further that the external sources give doses R^x_γ, R^x_n to a given organ x for γ and neutron radiation, respectively. If L^x rem is the average weekly dose permitted to organ x by the basic rules, then the total dose to organ x is

$$\left[\frac{\rho_{aA}}{(\mathrm{MPC})^x_{aA}} + \frac{\rho_{aB}}{(\mathrm{MPC})^x_{aB}} + \ldots + \frac{\rho_{wA}}{(\mathrm{MPC})^x_{wA}} + \frac{\rho_{wB}}{(\mathrm{MPC})^x_{wB}} + \ldots\right] L^x + R^x_\gamma + R^x_n \quad (22)$$

This does not exceed L^x provided

$$\frac{\rho_{aA}}{(\mathrm{MPC})^x_{aA}} + \frac{\rho_{aB}}{(\mathrm{MPC})^x_{aB}} + \ldots + \frac{\rho_{wA}}{(\mathrm{MPC})^x_{wA}} + \frac{\rho_{wB}}{(\mathrm{MPC})^x_{wB}} + \ldots + \frac{R^x_\gamma}{L^x} + \frac{R^x_n}{L^x} \leqslant 1 \quad (23)$$

and thus provides a criterion for assessing whether or not the exposure is in excess of that permitted by the basic rules. If organ x is not listed as an organ of reference in Table 1, and if an independent estimate of the corresponding MPC values is not available, the MPC based on total body may be used with the correction factor $L^x/0.1$, i.e. $L^x(\mathrm{MPC})^{T.B.}_a/0.1$ may be substituted for $(\mathrm{MPC})^x_a$ in such cases. In general it will be necessary to calculate the dose for all the organs for which the dose may reasonably be considered to be in excess of the prescribed limits. Often this may include the total body even though no one of the radionuclides irradiates a major portion of the body. Assuming that a major portion of the body is being irradiated at somewhat comparable rates, the calculation is essentially as before except that the MPC values based on total body are to be used. Thus the criterion is

$$\frac{\rho_{aA}}{(\mathrm{MPC})^{T.B.}_{aA}} + \frac{\rho_{aB}}{(\mathrm{MPC})^{T.B.}_{aB}} + \ldots + \frac{\rho_{wA}}{(\mathrm{MPC})^{T.B.}_{wA}} + \frac{\rho_{wB}}{(\mathrm{MPC})^{T.B.}_{wB}} + \ldots + \frac{R^{T.B.}_\gamma}{0.1} + \frac{R^{T.B.}_n}{0.1} \leqslant 1 \quad (24)$$

In effect this limits the average dose rate over the body to 0.1 rem/week. There may be some organs in which the dose rate exceeds 0.1 rem/week, but this is considered permissible so long as such organs do not constitute a major portion of the body. Of

The concentrations have been chosen to illustrate the case of a mixture which is below the permissible limit for one of the criteria (bone), but is barely in excess of the limit determined by another of the criteria (total body).

Criterion (23) applied to bone gives

$$\frac{\rho_{aA}}{(\mathrm{MPC})^{x}_{aA}} + \frac{\rho_{wA}}{(\mathrm{MPC})^{x}_{wA}} + \frac{\rho_{aB}}{(\mathrm{MPC})^{x}_{aB}} + \frac{\rho_{wB}}{(\mathrm{MPC})^{x}_{wB}} + \frac{0.1}{0.56}\left[\frac{\rho_{aC}}{(\mathrm{MPC})^{TB}_{aC}} + \frac{\rho_{wC}}{(\mathrm{MPC})^{TB}_{wC}}\right] + \frac{R^{x}_{\gamma}}{L^{x}}$$

$$= 0.06 + 0.038 + 0.2 + 0.13 + \frac{0.1}{0.56}(0.1 + 0.2) + \frac{0.065}{0.56} = 0.60 < 1.$$

Thus the average dose rate to the bone is about $0.60 \times 0.56 = 0.34$ effective rem/week and is therefore within the limits set for bone.

Criterion (24) for total body gives

$$\frac{\rho_{aA}}{(\mathrm{MPC})^{T.B.}_{aA}} + \frac{\rho_{wA}}{(\mathrm{MPC})^{T.B.}_{wA}} + \frac{\rho_{aB}}{(\mathrm{MPC})^{T.B.}_{aB}} + \frac{\rho_{wB}}{(\mathrm{MPC})^{T.B.}_{wB}} + \frac{\rho_{aC}}{(\mathrm{MPC})^{T.B.}_{aC}} + \frac{\rho_{wC}}{(\mathrm{MPC})^{T.B.}_{wC}} + \frac{R^{T.B.}_{\gamma}}{L^{T.B.}} =$$

$$0.02 + 0.015 + 0.04 + 0.013 + 0.1 + 0.2 + 0.65 = 1.038$$

and thus the calculation indicates that the mixture is slightly, though not significantly, in excess of the permissible limit for total body.

If the γ-source is removed, the dose rate to the bone becomes $0.48 \times 0.56 = 0.27$ rem/week while the dose rate to the total body is $0.39 \times 0.1 = 0.039$ rem/week. These dose rates are 48 per cent and 39 per cent of the corresponding limits, and thus the bone is now the critical organ. In this situation any or all of the concentrations could be increased by as much as a factor of 2 without exceeding the permissible limits.

9. Modifications required for other applications. The MPC values listed in Table 1 are intended primarily for occupational exposure and for the indicated types of exposure. Nevertheless, they are frequently used for a variety of other purposes. In most cases the conditions of exposure will not strictly conform to the conditions assumed for the calculation of these values. Thus great care and judgment should be used to insure that the departure from the conditions of occupational exposure assumed here are not so great as to completely invalidate the use of these values; some of the more common discrepancies that may often lead to large inaccuracies are mentioned.

A 50 year exposure period is assumed here and the exposure level is assumed to be constant. Thus a transient situation, e.g. fallout shortly after a nuclear detonation or a major reactor accident where the level of activity is rapidly decreasing, and even the

relative abundance of the different radionuclides may be changing, presents a hazard widely different from the constant level 50 year occupational exposure which is assumed. The measure of discrepancy is here so large that to attempt to correct for it amounts to a new calculation.

The $(\mathrm{MPC})_w$ values listed here may be applied to foods, but to use the $(\mathrm{MPC})_w$ for the 168 hr week without correction amounts to assuming that 2200 g of the individual's food, i.e. substantially all his food, is contaminated at this level and that this situation will persist for 50 years, or until equilibrium is reached in the body. Obviously, a correction factor to take account of the intake is needed, but to naïvely use the ratio of 2200 g to the gram intake of a particular food, e.g. butter, per day as correction factor amounts to assuming no other foods or beverages are contaminated. Again, the total situation must be considered and great judgment must be used in making such corrections.

Frequently the MPC values are used to obtain estimates of dose from large single intakes of a radionuclide. In many cases this is warranted, but there may well be many cases where the distribution in the body following an acute exposure to the nuclide is markedly different from the distribution pattern reached following chronic, low-level exposure. For example, many nuclides concentrate in bone with a long biological half-life which leads to a large bone burden of the nuclide after many years of exposure. Then the bone is the critical organ, although the fraction of the daily intake reaching the bone may be much smaller than that passing through the GI tract. For an acute single dose the GI tract may be the critical organ.

Many other factors may have a large effect in determining the proper value for a maximum permissible limit. The relative abundance or scarcity in the diet of other nuclides with similar chemical properties, the wide range of physiological differences as well as differences in habits, age and sex, and the chemical form of the radionuclide or the size of the particle to which it is attached, may account for large changes in the value of the MPC in some cases. Many of these factors as well as others are being carefully studied at the present time, and we may expect that our knowledge of their influence on the permissible levels will be more precise. In the present state of our knowledge, the modification or adaption of the values listed here for application to other situations than those specified by the exposure categories of the basic rules requires the careful consideration and mature judgment of competent experts in this field.

V. FACTORS NEEDED FOR CALCULATION OF MPC EQUATIONS

1. Effective energy. The effective energy term used in the formulas for calculating the values listed in Table 1 takes various forms as needed for the particular problem, i.e. $\Sigma E(\mathrm{RBE})$, $\Sigma E(\mathrm{RBE})n$, $\Sigma EF(\mathrm{RBE})n$, and sometimes simply ΣE. In these equations E is the total energy absorbed in the body organ per disintegration of the radionuclide. In these cases, all of the energy absorbed in the tissue in the process of radioactive decay (i.e. X, γ, α, β^-, β^+, e^- and atomic recoils) was included in the effective energy term with exception of the neutrino energy which is assumed to escape from the body. For β-radiation it was assumed that all the energy of each β is dissipated in the critical body organ. Except for very small organs this is justified

since it is generally the maximum dose that is of interest. Various methods have been developed for determining the distribution of β-ray energies and for finding the effective energy, but all are tedious and time consuming and a relatively simple empirical equation that gives results that are in most cases accurate within about 5 per cent was found.[27]

For β^--radiation the equation is

$$E = 0.33\, E_m f\left(1 - \frac{Z^{\frac{1}{2}}}{50}\right)\left(1 + \frac{E_m^{\frac{1}{2}}}{4}\right), \tag{25}$$

in which

Z = atomic number of the radionuclide emitting the β-ray;
f = fraction of the disintegrations of the type considered;
E_m = maximum energy (MeV) of the type considered.

For β^+-radiation the equation is,

$$E = 0.33\, E_m f\left(1 + \frac{E_m^{\frac{1}{2}}}{4}\right) + 2f(0.51)\,(1 - e^{-\sigma x}) \tag{26}$$

where

x = effective radius (cm) of the body organ containing the radionuclide (values are given in Table 8);
σ = total coefficient of absorption minus Compton scattering coefficient in cm^{-1} for the given photon energy;

2(0.51) arises from the energy of two 0.51 MeV gammas resulting from the annihilation process.

For other types of radiation, the following equations were used:

For γ-radiation $$E = E_m f\,(1 - e^{-\sigma x}) \tag{27}$$

For α-radiation $$E = E_m f \tag{28}$$

with E_m as the energy of the photon or α-particle.

For internal conversion, e^-

$$E = f\left[(E_\gamma - \eta)\left(\frac{\alpha_K}{1+\alpha_K}\right) + (\eta)\left(\frac{\alpha_K}{1+\alpha_K}\right)(1 - e^{-\sigma x}) + E_\gamma\left(\frac{1 - e^{-\sigma x}}{1+\alpha_K}\right)\right] \tag{29}$$

where

α_K = internal conversion coefficient for the K shell, etc.;
η = binding energy of the daughter element;
E_γ = γ-energy (MeV) of type considered.

For K and L capture X-radiation, the simplification is made that

$$E = f\eta(1 - e^{-\sigma x}) \tag{30}$$

For atomic recoils following α-emission

$$E = f\frac{\text{(energy of } \alpha\text{-particle) (mass of } \alpha\text{-particle)}}{\text{mass of recoiling daughter nucleus}} \tag{31}$$

RBE = relative biological effectiveness of the radiation; RBE is taken as 1 for β^--, β^+-, γ- and X-radiation and conversion electrons (it is set equal to 1.7 if the maximum energy $E_m \leqslant 0.03$ MeV for β^-, β^+ or ϵ^-), 10 for α-particles, and 20 for recoil atoms;

n = relative damage factor for radionuclides deposited in the bone. The relative damage factor, n, is defined in basic rule (b) and, a detailed discussion of its use, with examples, is given in Section IV.2;

F_i = the ratio at time t of the number of disintegrations per unit time of daughter atoms to the number of disintegrations per unit time of parent atoms in the critical organ. It is a factor that can be multiplied by the energy of the ith daughter so that it may be added to the energy of the other daughters and of the parent in order to obtain the weighted energy of a chain of radionuclides which is equivalent to that absorbed in the critical body organ by a single radionuclide. For the ith daughter,

$$F_i = \frac{\prod_{j=1}^{i} T_j/T_j^r}{1 - e^{-\lambda_0 t}} \sum_{n=0}^{i} \frac{T_n^i (1 - e^{-\lambda_n t})}{\prod_{\substack{p=0 \\ p \neq n}}^{i} (T_n - T_p)} \tag{32}$$

in which

λ_0 = total decay coefficient of the parent ($= 0.693/T_0$); the subscript, zero, refers to the parent isotope;

λ_i = total decay coefficient of the ith daughter;

T_i = total half-life of the ith daughter;

T_i^r = radioactive half-life of the ith daughter;

t = occupational exposure time (50 years).

In order to explain the meaning of the notation in the previous equations, equation (32) is expanded. For the parent $F_0 = 1$, for the first daughter

$$F_1 = \frac{T_1/T_1^r}{1 - e^{-\lambda_0 t}} \left[(1 - e^{-\lambda_0 t}) \frac{T_0}{T_0 - T_1} + (1 - e^{-\lambda_1 t}) \frac{T_1}{T_1 - T_0} \right] \tag{33}$$

and for the second daughter,

$$F_2 = \frac{T_1 T_2/T_1^r T_2^r}{1 - e^{-\lambda_0 t}} \left[\frac{(1 - e^{-\lambda_0 t}) T_0^2}{(T_0 - T_1)(T_0 - T_2)} + \frac{(1 - e^{-\lambda_1 t}) T_1^2}{(T_1 - T_0)(T_1 - T_2)} + \frac{(1 - e^{-\lambda_2 t}) T_2^2}{(T_2 - T_0)(T_2 - T_1)} \right] \tag{34}$$

etc., for all daughters of the chain. The appearance of these factors in the MPC equations is discussed in Section IV.4. In the case of radium isotopes which are daughters of a thorium isotope, recent experimental work has indicated that the radium daughter behaves as though it is absorbed into the blood. In these cases the factor f_2' for radium was included in the formula for F_1, F_2, etc.

The effective energy can be found by simply summing the component terms of $\Sigma\, EF(\mathrm{RBE})n$,

$$\Sigma\, EF(\mathrm{RBE})n = \Sigma_i F_i \Big[(\mathrm{RBE})_j f_j^i E_j^i + (\mathrm{RBE})_k f_k^i E_k^i n_k^i + (\mathrm{RBE})_s f_s^i E_s^i n_s^i + (\mathrm{RBE})_m f_m^i E_m^i n_m^i + (\mathrm{RBE})_v f_v^i E_v^i n_v^i + (\mathrm{RBE})_p f_p^i E_p^i + (\mathrm{RBE})_r f_r^i E_r^i n_r^i\Big] \tag{35}$$

where the subscripts j, k, s, m, v, p and r refer to γ, negatron, positron, α, internal conversion, electron capture, and α-recoil, respectively. The RBE of these radiations is specified above.

Effective energies[28] used for making the permissible exposure calculations of Table 1 are given in Tables 5 and 5(a). In Table 5(a) all the daughter nuclides are listed individually following the parent nuclide. The detailed listing is necessary here because the formulas for the GI tract require individual energies for each daughter nuclide. Also, the F_i factors necessitate separate listings for the entire chain, so that with the complete data as given, values for MPC and body burden for any mixture of parent and daughter radionuclides can be calculated easily.

2. Standard man data. In order that all MPC values be calculated on a common biological basis the so-called "standard man" or "average man" was defined.[29, 30] The first committee values were stipulated at the Chalk River Conference,[9] but later modified at the Sixth International Congress of Radiology,[31] the Harriman Conference on Permissible Dose,[32] and the Seventh International Congress of Radiology.[33] The values for the GI tract[34] (Table 11) and the chemical composition of the individual organs (Table 7) are further additions to the standard man. In Table 12 a few references have been listed, but it must be emphasized that these are only a few of those which were consulted. For a detailed study the reader should consult the references cited in *Bibliography for Biological Data** and the references listed below.[35–39]

3. Other biological and related physical terms. Other relevant biological and related physical terms that were used in the preparation of Table 1 appear in Table 12. For each element and radionuclide, the many distribution fractions, the concentration in the critical organs, the biological half-lives, etc., were gleaned from a voluminous amount of experimental data: data which, though great in mass, yielded in many cases a sparse amount of information concerning the specific quantities needed. Ideally, to establish satisfactory MPC values for occupational exposure, data are needed of lifetime exposure of humans to each of the radionuclides. However, not only are such data almost non-existent for man (see Section III for detailed

* *Health Physics*, Vol. 2, No. 3, 1959.

discussion) but they are extremely scarce for animals. As stated earlier, many of the biological factors used for the continuous exposure calculations of Table 1 were not obtained directly from continuous exposure animal data but of necessity were taken from single exposure data. Exploratory experiments[40] have indicated that extrapolation from single dose studies to the situation corresponding to continuous exposure is fairly satisfactory, if the single exposure data of retention in the critical body organ yield a curve having a long straight portion when plotted as a function of time on semilogarithmic paper. In general, the radionuclide does not seem to be uniformly bound in an organ and the retention curve is represented as a sum of exponentials. The component of longest half-life is generally the most significant for the long-term exposure case, and this is obtained by extrapolating back to time $t = 0$ the straight portion mentioned above. It sometimes happens that no data—not even data from single exposure of animals—are available for an element. When this is the case, it may be possible to obtain some of the desired information by assuming the existence of an equilibrium condition between the stable isotopes of the element in the critical body organ and in the food, water and air taken into the body from the environment,[10] i.e. set the amount ingested and deposited in the critical organ per day equal to the amount eliminated from it per day. For other cases where experimental data are not found, direct comparisons sometimes are made with elements that are chemically similar. Many equations and approximations—some of which are listed in this section—were used to check and cross-check the values given in these tables.

(a) I = average daily ingestion of an element (g/day).

(b) f_1 = fraction of the radionuclide passing from GI tract to blood.

(c) C = average concentration of the element in the critical organ (grams of element per gram of wet tissue).

(d) f_2' = fraction of the radionuclide passing from blood to critical body organ; in some cases this is chosen to represent only the component of longest biological half-life as mentioned above.

(e) f_2 = fraction of the radionuclide in the critical organ of that in total body. This fraction is required in the calculation of the maximum permissible body burden, q. The fraction f_2 is unusually difficult to find from limited experimental data, so it is fortunate that f_2 is not required for the calculation of MPC values. Various methods employing more easily measured fractions are often utilized for arriving at f_2; they are enumerated as follows:

(i) Under conditions of continuous exposure where equilibrium has been reached

$$f_2^x = \frac{q^x}{q^x+q^y+q^z+\ \ldots} = \frac{q^x}{q} \tag{36}$$

in which the superscripts x, y, z, etc., refer to different body organs, e.g. $q^x = \mu c$ in organ x, $q^y = \mu c$ in organ y, etc., and $q = \mu c$ in total body.

(ii) In cases where f_w and T can be found from single exposure data, f_2 can be determined by

$$f_2^x = \frac{T^x f_w^x}{T^x f_w^x + T^y f_w^y + T^z f_w^z + \ldots} \tag{37}$$

Sometimes when a long time has elapsed since the radionuclide was administered as a single exposure the biological half-lives for the various organs become approximately equal. In such cases

$$f_2^x = \frac{f_w^x}{f_w^x + f_w^y + f_w^z + \ldots} \tag{38}$$

(iii) For intravenous single exposure data equation (38) can be used by setting $f_w^x = f_1 f_2'^x, f_w^y = f_1 f_2'^y$ etc. Then,

$$f_2^x = \frac{f_2'^x}{f_2'^x + f_2'^y + f_2'^z + \ldots} \tag{39}$$

Equations (38) and (39) also apply in all cases where $T_r \ll T_b$ for organs x, y, z, etc.

(iv) For single exposure data

$$f_2^x = \frac{T^x f_w^x}{T^t(f_1 - f_w^u)} = \frac{T^x f_w^x}{T^t(f_w^x + f_w^y + f_w^z + \ldots)} =$$

$$\frac{T^x f_2'^x}{T^t(f_2'^x + f_2'^y + f_2'^z \ldots)} \tag{40}$$

in which the superscript, t, refers to total body and f_w^u = fraction of that ingested that goes rapidly to the urine. Where data are not available for f_w^u, the following approximations may be used;

$$f_2^x \geqslant \frac{T^x f_w^x}{T^t f_1} \tag{41}$$

$$f_2^x \geqslant \frac{T^x f_a^x}{T^t f_a^t} \tag{42}$$

(v) In the case of stable isotopes or radionuclides, where $T_r \gg T_b$,

$$f_2^x = \frac{m^x C^x}{m^t C^t}$$

Equations (37), (41) and (42) can be modified for this case so that

$$f_2^x = \frac{T_b^x f_w^x}{T_b^x f_w^x + T_b^y f_w^y + T_b^z f_w^z \ldots} \tag{43}$$

and

$$f_2^x = \frac{T_b^x f_w^x}{T_b^i f_1} \tag{44}$$

$$f_2^x = \frac{T_b^x f_a^x}{T_b^i f_a^i} \tag{45}$$

(f) f_a = fraction of that taken into the body by inhalation that arrives in the critical organ. For soluble material

$$f_a = (0.25 + 0.5 f_1) f'_2 \tag{46}$$

When the fraction f'_2, is unknown, it is replaced by f_2. It is sometimes convenient to write f_a in the form $f_a = (0.5 + 0.25/f_1)f_w$. MPC values are given in Table 1 for inhalation of insoluble and slightly soluble materials and in these cases a portion of the GI tract or the lung is usually the critical organ. Unless data are available for the inhalation of specific radioactive, insoluble dust particles, it is assumed in the case of the lungs that $f_a = 0.12$. Some of the inhaled radioactive material is swallowed, so that it irradiates the GI tract. In the case in which a portion of the GI tract is the critical tissue, the value of f_a is given by the equation, $f_a = 0.62$ for insoluble material and $f_a = 0.5$ for soluble.

(g) f_w = fraction of that taken into the body by ingestion that is retained in the critical organ. For ingestion of soluble compounds

$$f_w = f_1 f'_2 \tag{47}$$

f_2 is sometimes used instead of f'_2 if no better information is available. For ingestion of insoluble compounds a portion of the GI tract is the critical tissue.

(h) T_b = biological half-life or the time required for half of the element or radionuclide to be eliminated by biological processes. When T_b cannot be found from experimental data for a particular radionuclide, the assumption is made that the radionuclide has the same biological elimination time as the stable element. Assuming the existence of an equilibrium condition between the stable element in the food and water and the stable element in the critical body organ, the grams eliminated per day may be set equal to the grams deposited per day. It follows then that for a stable element

$$T_b = \frac{0.693\, m\, C}{I f_w} \tag{48}$$

In the above equation f_w may be replaced by f_a if inhalation rather than ingestion is responsible for the deposition of the stable element in the body. For insoluble material in the lungs, T_b is taken as 120 days for all radionuclides except plutonium and thorium, in which case $T_b =$ 1 year and $T_b = 4$ years, respectively, were used.

(i) $T_r =$ radioactive half-life.

(j) $T =$ effective half-life. Because by definition the total decay coefficient is equal to the sum of the biological and physical decay coefficients, i.e. $\lambda = \lambda_r + \lambda_b$,

$$T = \frac{T_b\, T_r}{T_b + T_r} \tag{49}$$

For a radionuclide equation (48) becomes

$$T = \frac{0.693\, m\, C}{I f_w} \tag{50}$$

in which $C =$ grams of radionuclide per gram of organ. If $T_r \gg T_b$, C for the stable element is approximately equal to C for the radioelement.

As explained previously, single exposure data can be used satisfactorily to find biological constants for chronic exposure if the retention data plotted on a semi-logarithmic graph as a function of time of exposure yield a curve with a long straight portion following the initial rapid elimination. If the data are not corrected for radioactive decay, the effective half-life in such cases is related to the ordinate b of the curve, taken at the beginning of the straight portion and ordinate c taken at some later time by the expression

$$T = \frac{0.693\, t}{\ln b/c} \tag{51}$$

in which $t =$ time interval between b and c

In any two organs x and y,

$$\frac{f_2^x}{f_2^y} = \frac{m^x\, C^x}{m^y\, C^y} \tag{52}$$

and,

$$\frac{T^x}{T^y} = \frac{f_2^x f_w^x}{f_2\, f_w^y} \tag{53}$$

As indicated earlier, the critical body organ is that organ receiving the radionuclide that results in the greatest body damage. However, in most cases it is the body

organ that accumulates the greatest concentration of the radionuclide. Having selected the critical body organ, it is useful to make a check to determine whether or not this organ has an above average concentration. If the concentration in organ x is greater than the average concentration in the rest of the body

$$\frac{m(1 - f_2^x)}{(70{,}000 - m) f_2^x} \leqslant 1 \tag{54}$$

APPENDIX

Concentrations in air and in water based on a power function model. Although the formulas used to calculate the maximum permissible concentrations assume that the biological elimination follows a simple exponential function, i.e. the fraction of organ burden eliminated per day is constant, cognizance is taken of the fact that many data[41] support the view that the fraction of the body burden excreted per day varies inversely with the time and could best be represented by a power function. Following a single injection of certain bone-seeking radionuclides, the body burden has been expressed by

$$R(t) = A\, t^{-n} \qquad t \geqq 1 \tag{55}$$

where $R(t)$ = fractional retention t days after injection;
A = normalized fraction of injected dose retained at end of unit time;
n = a constant.

Ingested or inhaled material may not be retained to the same degree, therefore a factor, f_1, should be included to designate the fraction of ingested radionuclide which reaches the blood stream. If the radionuclide is long-lived so that radioactive decay can be neglected, then the body burden after an amount, a, has been ingested per day for T days is given by

$$q = A\, a f_1 \int_0^T (T - \tau)^{-n}\, d\tau = \frac{A\, a f_1}{1 - n} T^{1-n}\, \mu c \tag{56}$$

This equation assumes n is not close to 1. Otherwise the integration should extend from 1 day to T days and the contribution of the first day added. In terms of the previous notation $a = P/f_w = 750$ M $= 750$ (MPC)$_w$ for ingestion or $a = P/f_a = 6.9 \times 10^6$ (MPC)$_a$ for inhalation, and T is the period of occupational exposure which is set at 50 years for the values recorded in Table 1.

If the radioactive half-life of the radionuclide is of the same order as T, it may be taken into account also. If the body burden following a single intravenous injection, $R(t)$, is a power function, the fraction eliminated per day is given by

$$\frac{dR}{dt}/R = -\frac{n}{t} \tag{57}$$

which represents only the biological elimination of the radionuclide because experiments determining the best values for A and n are generally of short duration as compared to the radioactive half-life of the radionuclides here considered (Sr, Ra, Pu and U); thus, including radioactive decay

$$dR/dt = -\frac{n}{t} R(t) - \lambda^r R(t) \tag{58}$$

where λ^r is the radioactive decay constant of the radionuclide in days.

The integral of this equation with $R(1) = A$ readily is found to be

$$R(t) = A\, t^{-n}\, e^{-\lambda^r (t-1)} \quad t > 1 \tag{59}$$

Hence, if the radionuclide is undergoing appreciable radioactive decay while it is being eliminated from the body according to a power function, the body burden under the same conditions as before is given by

$$q = a\, A f_1 \int_0^T (T - \tau)^{-n}\, e^{-\lambda^r (T-\tau-1)} = a\, A f_1 \int_0^T u^{-n}\, e^{-\lambda^r (u-1)}\, du\ \mu c \tag{60}$$

or

$$(\mathrm{MPC})_a = \frac{q}{6.9 \times 10^6\, A f_1 \int_0^T u^{-n}\, e^{-\lambda^r (u-1)}\, du}\ \mu c/cm^3 \tag{61}$$

and

$$(\mathrm{MPC})_w = \frac{q}{750\, A f_1 \int_0^T u^{-n}\, e^{-\lambda^r (u-1)}\, du}\ \mu c/cm^3 \tag{62}$$

This integral may be evaluated with the help of a table of the incomplete γ-function.[42]

In case the radionuclide has daughters which must be taken into account, the power function estimate of elimination still may be applied. In principle, the daughter elements might be eliminated at rates quite different from those of the parent, i.e. the constant n may be different for different elements of the chain. In such cases the value of n would vary from element to element in the chain. The formulas for this case would be similar to those given above.

For example, in the case of Ra^{228} it seems desirable to consider the elements of a chain. Because all these elements are held very tenaciously in the body, the daughter elements with radioactive half-lives of a few hours or days may be considered to decay immediately and thus only the case of a chain of two radionuclides is discussed. Also the same value of n is assumed for each of these radionuclides.

Letting $R_0(t)$ and $R_1(t)$ denote the body burden (μc) of the parent and the daughter radionuclide, respectively, at time t days following injection of 1 μc of the parent, the differential equations governing the changes with time are:

$$\frac{dR_0}{dt} = \frac{-n}{t} R_0(t) - \lambda_0^r R_0(t) \tag{63}$$

$$\frac{dR_1}{dt} = \frac{-n}{t} R_1(t) - \lambda_1^r R_1(t) + \lambda_1^r R_0(t) \tag{64}$$

The solution which gives an amount A for the parent and 0 for the daughters at $t = 1$ is given by,

$$R_0(t) = A\, t^{-n}\, e^{-\lambda_0^r (t-1)} \tag{65}$$

$$R_1(t) = \frac{A\, \lambda_1^r\, t^{-n}}{\lambda_1^r - \lambda_0^r}\left[e^{-\lambda_0^r (t-1)} - e^{-\lambda_1^r (t-1)}\right] \tag{66}$$

Except for the presence of the factor $A\, t^{-n}$ these equations are identical with the expanded form of equation (9). This solution is valid only if $n\ 1 \ll$ but this is true in all the practical cases considered here. The choice of the solution where $R_0(1) = A$ and $R_1(1) = 0$ neglects the formation of the daughter radionuclides during the first day. Because it is only applied here to radionuclides of rather long radioactive half-life, and because the power function does not represent adequately the behavior of the radionuclide for short periods of time after injection, this neglect seems justified.

If an amount, a μc, enters the blood per day during a period of T days, the body burden of the ith isotope at the end of T days is given by

$$a \int_0^T R_i(T - t)\, dt \tag{67}$$

and this leads to an incomplete γ-function which may be evaluated as before. From these estimates of body burden, the $(\mathrm{MPC})_a$ and $(\mathrm{MPC})_w$ can be estimated by the method used in deriving equations (61) and (62).

At present the use of a power function is possible in only a few cases. There is some indication that it does not represent precisely the true situation since the exponent n has been found to vary with time.[43] However, for the radionuclides with long physical half-lives, the power function does seem to represent adequately the available long-term data. Unfortunately, its metabolic significance remains unexplained, and it does not seem desirable to extrapolate an empirical formula far beyond the range where it has been verified experimentally. For comparison, MPC values have been computed both according to the exponential model and the power law for the radionuclides of Sr, Ra, Pu and U which have an effective half-life exceeding 20 days. In these cases, the Committee has considered the MPC values obtained both by the power function as well as by the exponential method in

selecting the values listed in Table 1. The values of the constants considered and the MPC values obtained in the case of the more important isotopes of these four elements are listed in Table *B*. These values were selected by a Subcommittee on the Power Function.*

Table B. MPC values as calculated by the power function model
(168 hr/week)

Radionuclides and retention constants	$(MPC)_w$ ($\mu c/cm^3$)	$(MPC)_a$ ($\mu c/cm^3$)	Critical organ
Strontium			
$A = 0.65$, $n = 0.35$			
Sr^{85}	6×10^{-3}	5×10^{-7}	Bone
Sr^{89}	4×10^{-4}	4×10^{-8}	Bone
Sr^{90}	8×10^{-6}	7×10^{-10}	Bone
Strontium			
$A = 0.95$, $n = 0.25$			
Sr^{85}	3×10^{-3}	2×10^{-7}	Bone
Sr^{89}	2×10^{-4}	2×10^{-8}	Bone
Sr^{90}	6×10^{-6}	5×10^{-10}	Bone
Radium			
$A = 0.54$, $n = 0.52$			
Ra^{226}	1×10^{-6}	1×10^{-10}	Bone
Ra^{228}	2×10^{-6}	1×10^{-10}	Bone
Uranium			
$A = 0.72$, $n = 0.80$			
U^{238}	8×10^{-4}	4×10^{-11}	Kidney
U–nat	8×10^{-4}	4×10^{-11}	Kidney
Plutonium			
$A = 0.99$, $n = 0.01$			
Pu^{238}	5×10^{-5}	6×10^{-13}	Bone
Pu^{239}	4×10^{-5}	5×10^{-13}	Bone
Pu^{240}	4×10^{-5}	5×10^{-13}	Bone
Pu^{241}	2×10^{-3}	3×10^{-11}	Bone
Pu^{242}	5×10^{-5}	6×10^{-13}	Bone

In the cases considered, the power function method seems to yield a higher estimate of the MPC values than does the exponential method. Since, in principle, the retention data can be fitted with a multiple exponential curve, this undoubtedly is in large part due to conservatism in assigning a long biological half-life and a rather large value to the fraction of material in the blood that has the long half-life, i.e. to f_2'. While the MPC values listed in the accompanying table were considered by the

* The data in Table *B* were developed and agreed upon by a special subcommittee which was organized to evaluate the application of the power function in obtaining MPC values. The members were: W. H. Langham, Chairman, E. C. Anderson, P. Harris, J. W. Healy, W. P. Norris and W. S. Snyder.

Committee in making their final decision, they are not to be considered as recommended values. They are listed to indicate that the Committee has considered carefully this method of estimation and to stimulate research concerning the interpretation and validity of this model. The presentation of the biological data in Table 12 on the basis of the exponential model is in large part dictated by the desire to give a unified and economical presentation of the material.

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33. *Seventh International Congress of Radiology and Associated Conferences of the International Commission on Radiological Protection.* (Meeting held in Copenhagen, Denmark, 13 to 24 July, 1953.)
34. See reference Po–5.
35. A Joint Meeting of the Delegations of the United States, Canada and Great Britain was held at Buckland House, near Faringdon, Berkshire, on August 4, 5 and 6, 1950. (Minutes of meeting prepared by L. D. Marinelli for the United States delegation.)
36. *Conference on Radiobiology and Radiation Protection of the International Commission on Radiological Protection.* (Held on 15 September, 1952, at the Institute of Radiophysics, Stockholm, Sweden.) (Meeting held on 18 September, 1952, in Uppsala, of Members of the Commission attending the Stockholm Radiological Conference.)
37. *Eighth International Congress of Radiology.* (Held in Calle del Oio, Mexico, 22 to 28 July, 1956.) *Joint Meeting of ICRP/ICRU* (re: Medical Exposures) 31 October to 7 November, 1956, New York.
    Meeting in Geneva, Switzerland, 23 April to 1 May, 1957 (Task Groups).
    Exposure of man to ionizing radiation arising from medical procedures: an inquiry into methods of evaluation. A report of the ICRP and ICRU. *Phys. in Med. and Biol.*, *2*, 107–151 (1957).
38. *Joint Meeting of United States Members of Internal Dose Subcommittees of NCRP and the ICRP* 10 to 11 December, 1956, Washington, D.C.
39. *Meeting of ICRP.* (Held in New York, 3 to 12 March, 1958.)
40. See references Ma–2 and Th–18.
41. See references Ber–4, Hy–6, Ln–12, Mn–11, Mn–13, No–7, No–9 and Sny–1.
42. See references Jh–1, Pea–1 and Pea–2.
43. See reference War–2.