15 February 1963, Volume 139, Number 3555 SCIENCE

Permissible Exposure to Ionizing Radiation

Many factors, some imponderable, contribute to the estimation of a maximum permissible dose.

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During the past 20 years, radiation hazards have been given widespread attention and have occasioned great concern on the part of both scientists and of the public. General awareness of these radiation hazards has forced the nuclear industry to become one of the safest of large, modern industries. An important factor in the prevention and control of radiation hazards was the development and practice of health physics during the early years of World War II. The health physicist's primary concern is understanding the mechanism of radiation damage, determining and enforcing safe and reasonable exposure levels, developing monitoring techniques, and implementing control measures to provide adequate protection against radiation. The goal of the health physicist is to keep exposure levels as low as practical and still obtain the benefits from the use of ionizing radiation. His guiding principle is that any unnecessary man-made exposure is too much exposure. He recognizes the serious consequences of large over-exposure, but he believes that constant vigilance and intelligent planning can reduce radiation damage so that the evident advantages of the proper use of nuclear energy and other sources of ionizing radiation may be obtained.

There have always been sources of ionizing radiation in the natural background of man, and in spite of the inevitable exposure he has evolved to his present stage of development. The natural background exposure results from both external and internal sources. The principal sources of external exposure are cosmic radiation and radiation from naturally occurring uranium, thorium, and actinium chain products. The internal exposure results primarily from K^{40}, C^{14}, Ra^{226}, and Ra^{228} and their daughter products that are deposited in the body and from Rn^{222} and Rn^{220} and their daughter products that are inhaled. The exposure to natural background radiation varies considerably and depends upon where one lives, what one eats, and the structural material of his home. Although no extensive world survey data are available, the average gonad dose to man from background radiation is probably about 100 mrem/yr, but in a few regions it is greater than 1000 mrem/yr. Lung exposure is usually much higher—500 to 1000 mrem/yr and in some cases may exceed 5000 mrem/yr. Epidemiological studies of population groups exposed for generations to unusually high levels of natural background radiation might provide a sounder basis for establishment of levels of maximum permissible exposure. Such exposure groups (for which adequate control groups might be available) could be (i) communities that use sources of water and food with a radium content more than 10 times the average, (ii) populations that inhabit monazite sand regions, such as the Kerala regions of India, where the external dose is 4 to 30 times the average for the world, and (iii) persons who live in homes made of certain structural materials such as concrete blocks containing uranium-bearing shale from which the Rn^{222} could escape continuously into the dwelling.

One of the earliest records of damage to man from ionizing radiation comes from the descriptions of bronchogenic epithelial carcinomas which appeared in workers 10 to 20 years after the workers had been exposed to radon in the Schneeberg cobalt mines of Saxony and the Joachimsthal pitchblende mines of Bohemia. These mines contained large concentrations of uranium and, in addition, cobalt, lead, arsenic, and silicon, any one of which might be expected to be an industrial hazard. However, the one factor (*1*) which seemed primarily responsible for the high incidence of lung cancer was the radiation from the daughter products of uranium, namely, Ra^{226}, Rn^{222}, Po^{218}, and others. As early as 1500 a high incidence of lung disease was recognized among the miners. In 1879 Herting and Hesse (*1*) noted malignant growths in the lungs of miners during postmortem examinations and in 1911 Arnstein (*1*) showed that these malignancies were carcinomas. Becquerel (*2*) learned from experience the need for radiation protection. After carrying in his vest pocket a sealed glass tube of radium-bearing barium chloride, he developed an erythema on his chest which ulcerated and left a scar when it healed. Madame Curie (*2*) developed radiation burns on her hands as a result of handling small tubes of radium. By far the most serious exposures were those to young women engaged in painting radium dials for timepieces

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during the period of World War I. The first recorded fatality (*3*) attributed to this particular exposure was in 1925 and since that time over 50 such cases of radium-induced cancer have been recorded in the United States.

The unfortunate experience of a few of the thousands of radium-dial painters attracted attention to this problem and led to the establishment, in 1941, of the maximum permissible body burden of radium of 0.1 μg by an Advisory Committee of the National Bureau of Standards (*4*). This was the first radiation standard set for internal exposure and, interestingly, even after 21 years of study and human experience it is still the maximum permissible body burden for Ra^{226}. This value is the current standard reference for determining maximum permissible body burden values for bone-seeking radionuclides such as Sr^{90} and Pu^{239}.

ICRU, ICRP, NCRP, and FRC

In 1925 the first International Congress of Radiology (ICR) established the International Commission on Radiological Units (ICRU) and in this same year two scientists, A. Mutscheller and R. M. Sievert, recommended a maximum permissible dose from x-ray or radium of one-tenth of an erythema dose per year (*5*). At that time the appearance of erythema was most often used as a criterion for determining values for permissible exposure. Also, at that time most of the exposure was to x-rays of relatively low voltage, so this amount probably corresponds to about 30 roentgens per year. In 1928 the ICR formed the International Commission on Radiological Protection (ICRP) which published the first set of international recommendations for protection from ionizing radiation (*6*). Also in 1928 a great step forward was made when the ICRU adopted the roentgen (r) as the unit of exposure.

Under the guidance of L. S. Taylor (*6*) and through the auspices of the National Bureau of Standards the National Committee on Radiation Protection (NCRP) was formed in 1929. In 1934 the ICRP adopted a maximum permissible dose rate of 0.2 r per day and in the same year the handbook published by NCRP (*7*) listed the maximum permissible dose rate as 0.1 r per day.

The ICRP has been the recognized authority for fixing the values of maximum permissible exposure to ionizing radiation on an international level and the NCRP has served a similar role in the United States. Initially, these two organizations were concerned chiefly with problems of occupational exposures of doctors, nurses, medical technicians, and so forth. The development of the nuclear energy industry during World War II aroused interest in the need for increased protection from ionizing radiation, and the two organizations were reorganized for the purpose of providing recommendations for the protection of all occupational groups and the general population from any source of ionizing radiation.

In 1959, the Federal Radiation Council (FRC) was authorized by Congress to . . . "advise the President . . . with respect to radiation matters directly or indirectly affecting health. . . ." The FRC has recognized the authority and preeminence of the NCRP and the ICRP in the field of radiation protection and has worked with many ad hoc committees and discussion groups that included members of these organizations. As instructed by Congress, it "consults qualified scientists and experts in radiation matters, including the president of the National Academy of Sciences, the chairman of the NCRP and qualified experts in the field of biology and medicine and in the field of health physics." The FRC has published three reports (*8*) which are endorsements of the maximum permissible exposure values established by the NCRP and ICRP. In addition to consulting with scientists, it is to be expected that the FRC consults with economists, lawyers, teachers, ministers, sociologists, and business executives among others so that it will be in a position to weigh the benefits against the hazards in establishing a national policy relative to radiation exposure.

Considerations in the Selection of Maximum Permissible Exposure Values

The levels of maximum permissible exposure (MPE) to ionizing radiation as recommended by the NCRP, the ICRP, and the FRC are intended to prevent or limit two kinds of radiation damage, that which may be classed as a "threshold type" and that which is present to some degree in all cases of radiation exposure. Radiation sickness and LD-50-30 (dose which is required to cause 50 percent lethality in 30 days after a single total-body exposure) are threshold types of radiation damage which become manifest only when the dose exceeds a relatively large threshold value. Genetic mutations, leukemia, bone tumors, and life-shortening are commonly considered (but not proved) to be types of damage that increase monotonically with the dose and do not have a threshold dose below which such damage does not result.

Many of the early publications on radiation hazards referred to the "tolerance dose". This was interpreted by some persons as a level set safely below the threshold dose at which radiation damage would ensue. Some types of radiation damage are not immediately measurable, and each increment of dose merely increases the probability that one or more types of radiation damage will occur in the lifetime of an individual. Thus to exceed a certain prescribed dose level does not necessarily mean that damage from these types of radiation will be detected in an individual. When this became evident the expression tolerance dose was replaced by "maximum permissible exposure" (or "maximum permissible dose"). More recently, the FRC (*8*) has replaced maximum permissible exposure with "radiation protection guide" to avoid the impression that there is a "single permissible or acceptable level of exposure without regard to the reason for permitting the exposure." Regardless of the intentions or merits for these changes, the words "tolerance," "maximum permissible," and "guide" are used and understood by most persons to mean the maximum acceptable level for exposure to ionizing radiation under usual conditions of operation. For practical purposes and legal reasons, maximum permissible exposure values must be established for general operations and applications and all persons subject to exposure should regard these levels as limits that are not to be exceeded except in emergencies.

In 1954, the NCRP (*9*) defined the maximum permissible dose (MPD) as "the dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." Appreciable bodily injury was defined as "any bodily injury or effect that the average person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well being of the individual." In

1959 the NCRP *(10)* advanced the concept of MPD: "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 to the individual or to present a hazard more severe than those commonly accepted in other present day industries." In 1958 the ICRP *(11)* very carefully defined: "The permissible dose for an individual is that dose, accumulated over a long period of time or resulting from a single exposure which in the light of present knowledge, carries a negligible probability of severe somatic or genetic injuries; furthermore, it is such a dose that any effects that ensue more frequently are limited to those of a minor nature that would not be considered unacceptable by the exposed individual and by competent medical authorities, Any severe somatic injuries, such as leukemia, that might result from exposure of individuals to the permissible dose would be limited to an exceedingly small fraction of the exposed group; effects such as shortening of life span, which might be expected to occur more frequently, would be very slight and would likely be hidden by normal biological variations. The permissible doses can, therefore, be expected to produce effects that could be detectable only by statistical methods applied to large groups." In 1960, the FRC *(8)* defined: "Radiation Protection Guide, RPG, is the radiation dose which should not be exceeded without careful consideration of the reasons for doing so; every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable." Although the above definitions leave many questions unanswered, they nevertheless help to interpret the meaning of MPD as intended by the NCRP and the ICRP and the meaning of RPG as defined by the FRC.

Definition of Units

Before proceeding with a discussion of specific values of MPE or MPD the commonly accepted and universally used units of ionizing radiation should be defined. The ICRU *(12, 13)* defines the roentgen (r) as the unit of exposure of x- or γ-radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign. The ICRU defines the rad as the unit of absorbed dose, and 1 rad corresponds to 100 ergs per gram of medium. In radiation protection work (unless otherwise specified) 1 rad corresponds to the absorption per gram of soft tissue of 100 ergs of energy delivered by ionizing radiation. The rad as a unit of absorbed dose may be applied correctly to any type of energy deposition by any kind of ionizing radiation. However, the biological sequelae of radiation exposure do not always correlate well with the absorbed dose (rad) that is delivered. In general, the biological effect varies with many factors such as the dose rate, accumulated dose, linear energy transfer of the radiation (LET), and the body organ under study. There are many common situations where an absorbed dose due to neutron or other heavy-particle radiation appears more damaging than an equal absorbed dose of x-rays. To take account of such differences in the biological effectiveness the ICRP and the ICRU introduced the rem as a unit of RBE dose. By definition, the RBE dose in rems equals the dose in rads multiplied by the relative biological effectiveness (RBE). The RBE of a given radiation field is defined as the ratio of absorbed dose (in rads) from the reference x-rays to the absorbed dose (in rads) from the given radiation field required to produce the same effect as the reference x-rays. In most cases the reference x-rays have been those from 200 to 250 kv x-radiation or γ-radiation from Co^{60}, although efforts have been made rather arbitrarily to assign RBE = 1 for radiation for which the linear energy transfer is < 3.5 kev/μ of water. It was hoped that by the use of the RBE concept biological effects of neutrons and other heavy particle radiation might be compared with effects of x-rays. However, the RBE factor, a rather complicated concept, depends upon almost all conditions of the exposure and can be considered as only imperfectly known for most situations of human exposure. The interested reader may consult Storer *et al. (14)* for a summary of the experimental evidence of values of RBE.

For monitoring purposes and particularly for internal dose applications,

Table 1. Recommended permissible dose equivalent to body organs of occupational workers exposed to ionizing radiation. These values are in addition to doses from medical and from background exposure. The unit of dose equivalent *(13)* used in this table is the rem defined as: (No. of rem) = (No. of rad) × (RBE) × n. In column 3, N is the age. Reference numbers are in italics.

Maximum dose equivalent in any 13 wk*	Average dose equivalent† in 1 yr	Accumulated dose equivalent to age $N > 18$ years
	Blood-forming organs	
3 *(11, 20, 21)*	5 *(11, 16, 20)*	5(N-18) *(11, 16, 20, 21)*
	Total body	
3 *(18, 16, 20, 10, 21)*	5 *(18, 20, 10)*	5(N-18) *(18, 16, 20, 10, 21)*
	Head and trunk	
3 *(20, 21)*	5 *(20)*	5(N-18) *(16, 21)*
	Gonads	
3 *(11, 18, 20, 10, 21)*	5 *(11, 18, 16, 20, 10)*	5(N-18) *(11, 18, 16, 20, 10, 21)*
	Lenses of eyes	
3 (11, 22‡, 20, 10, 21)	5 *(11, 22‡, 16, 20, 10)*	5(N-18) *(11, 22‡, 16, 20, 10, 21)*
	Skin	
8 *(11, 18)* 10 *(10, 23, 21)*	30 *(11, 18, 20, 10, 23, 19)* (21, ‖)	30(N-18) *(11, 18, 10,* §, ‖)
	Thyroid	
8 *(11, 18, 10)* 10 *(21)*	30 *(11, 18, 20, 10, 21)*	30(N-18) (§)
	Feet, ankles, hands, forearms	
20 *(11)* 25 *(21, 10, 20)*	75 *(11, 20, 10, 19, 21)*	75(N-18) (§)
	Bone	
10 (§)	30 *(18, 10, §)*	30(N-18) (§)
	Other single organs	
4 *(11, 18)* 5 *(21)*	15 *(11, 18, 20, 10, 19, 21)*	15(N-18) (§)

* These values may be used for the accumulated short-term exposures in any 13-week interval *(22)*. † These values may be used for a planned emergency exposure *(22)*. ‡ The 1962 ICRP meeting in Stockholm recommended that exposures of lenses of eyes be restricted to this limit only in the case of high LET radiation, for example, from α, protons, neutrons, and so forth. For low LET radiation the ICRP values applicable to the eyes are given after "other single organs." § Implied but not stated explicitly *(11, 18, 20, 10, 21)*. ‖ I interpret this to apply only when dose is limited to skin; for example, it applies to low energy β-radiation external to body or originating in skin.

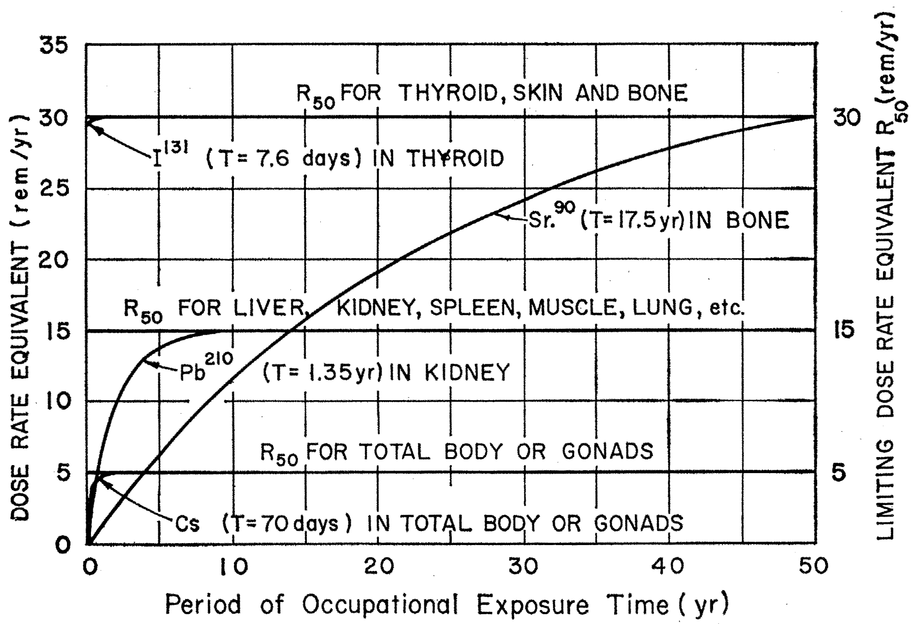

Fig. 1. Dose rate equivalent to various critical body organs for intake lasting 50 years at the MPC for occupational workers. (The curve labeled Cs refers to Cs^{137}.)

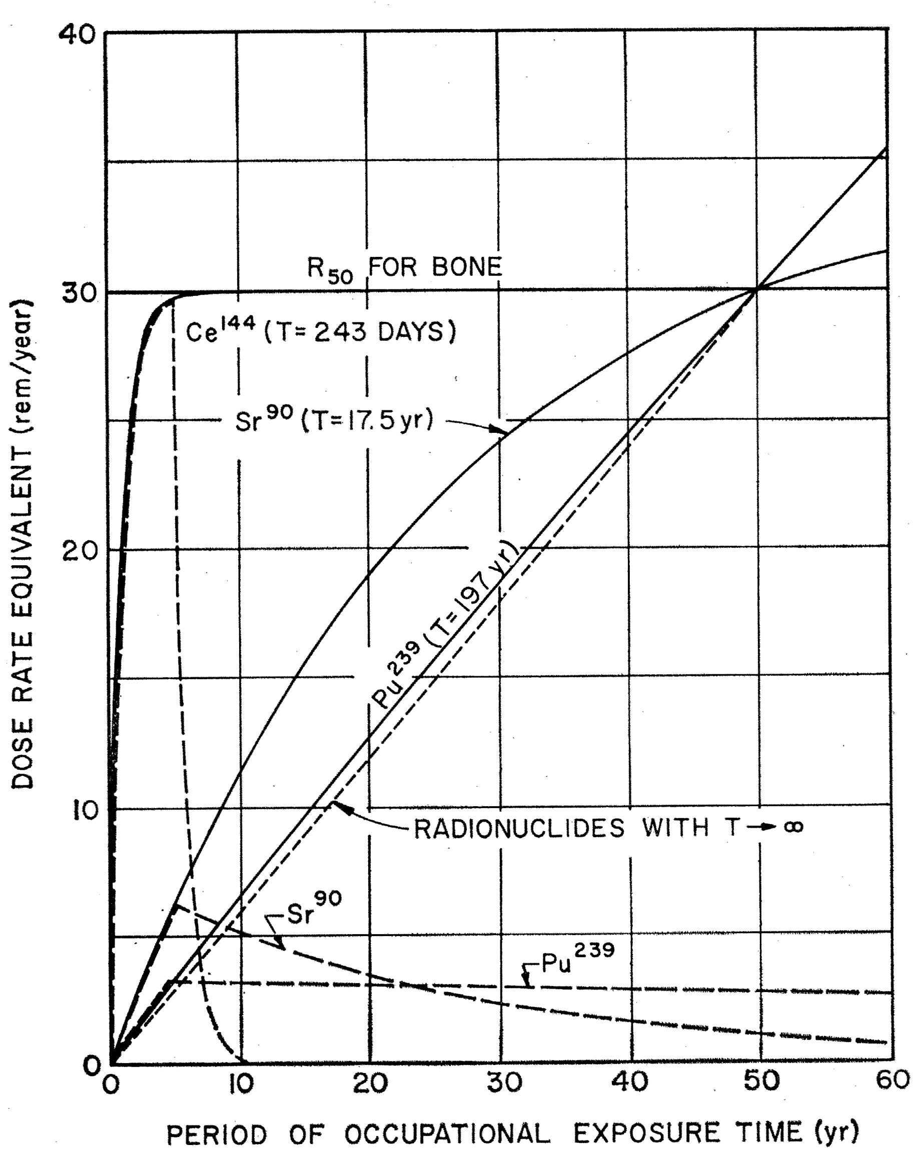

Fig. 2. Dose rate equivalent to bone for intake lasting for 50 years and for 5 years at the MPC for occupational workers.

"RBE dose" as presently defined has proved to be somewhat awkward and rather inadequate. In calculating the dose equivalent for various bone-seeking radionuclides the NCRP and the ICRP introduced the relative damage factor, *n*. In animal experiments certain bone-seeking radionuclides produced greater biological damage to bone than Ra^{226} for the same RBE dose. Since, as stated above, a body burden of 0.1μg of Ra^{226} is the standard for determining the maximum permissible body burden for other bone-seeking radionuclides, this experimental factor *n* was introduced in finding the dose equivalent needed for these calculations. This relative damage factor *n* is a composite of (i) nonuniform deposition in the bone, (ii) greater essentialness of the tissues of the bone that are damaged, and (iii) greater radiosensitivity of the damaged tissues of the bone.

In order to avoid confusion, the ICRU in its November 1962 (*13*) report recommended that RBE be used only in radiobiology and, that for radiation protection purposes, the term quality factors (QF) should be used to express the modification of the biological effect due to LET, *n*, and other conditions. For radiation protection applications, the expression "RBE dose" is to be replaced by the quantity "dose equivalent" which is given in rem units. Dose equivalent is expressed by the equation,

$$\text{Dose equivalent (in rem)} = \Sigma \text{ absorbed dose (in rad)} \times QF_1 \times QF_2 \times \ldots \quad (1)$$

in which QF_1 refers to RBE as used in previous publications as it related to LET; QF_2 refers to *n* as applied to internal dose problems or to other factors. Specific values of QF_2 or *n* are given later in this article.

Maximum Permissible Exposure Values

There have been reductions in the maximum permissible exposure limits of the total body to ionizing radiation by a factor of 10 or more during the past few years. These reductions were not the result of positive evidence of damage from the amounts previously recommended; they represent an increased awareness of the hazards of ionizing radiation and a greater concern for nonthreshold types of radiation damage. It has become increasingly evident that there may not be a threshold dose below which no radiation damage could result. The present rate for occupational exposure which was recommended by the ICRP in April 1956 (*15*) and the NCRP in January 1957 (*16*) is 5 rem/yr, which is equivalent to 0.1 rem/week for a 5-day work week. The present dose limit of ionizing radiation to the total body for the population-at-large from man-made sources of ionizing radiation, as suggested by the ICRP in September 1958 (*11*), is 5 rem/30 yr or 0.003 rem/week. This value does not include doses from medical and background exposure.

The recommended permissible dose of ionizing radiation to the various organs of the body of the occupational worker is summarized in Table 1. These values apply to both external and internal exposure. Values are given for the maximum dose equivalent in any 13-week period, for the average annual dose equivalent, and for the accumulated dose equivalent to age N, where N is for workers over 18 years old. Except for minor differences in some of the values in the first column, there is complete agreement in the recommended dose limits. These differences do not represent any disagreement but result from the fact that the NCRP, and later the FRC, decided to set the maximum dose for any 13-week period in these cases at 1/3 the annual dose limit; the ICRP, meeting at a different time and place, chose values slightly, but not significantly, smaller.

The values of permissible dose recommended by the ICRP for several exposure groups are summarized in Table 2, which also lists the factors by which the occupational exposure values must be multiplied to obtain these values. The report of an ad hoc committee of NCRP (*17*) in 1960 gave a detailed explanation of why the permissible dose to large groups should be less than that to the relatively small occupational group. Perhaps the most commonly quoted figures in Table 2 are the factors of 1/100 as applied to the occupational exposure value of 5 rem/yr to obtain the value of 0.05 rem/yr for the average exposure to the gonads or total body from radionuclides deposited within the bodies of members of the population-at-large, and the factor of 1/30 as applied to the occupational exposure value of 15 rem/yr to obtain the corresponding value of 0.5 rem/yr for the average exposure to most organs of the body from internally deposited radionuclides. At the 1962 ICRP meeting in Stockholm, Sweden, group B(C) was included as a part of group C since there seemed to be no reason to give it separate treatment. At present NCRP has only set MPE values for the occupational worker but has suggested that the maximum values for the population-at-large be 1/10 of the occupational MPE. The FRC (*8*) has endorsed several of the values in Table 2 and has set three "ranges" of exposure for environmental levels in such a way that the top of range II corresponds essentially to the value of permissible exposure to the average member of the population-at-large. At present, the FRC has given values for the top of range II of 100 $\mu\mu$c/day for I^{131}, 20 $\mu\mu$c/day for Ra^{226}, 200 $\mu\mu$c/day for Sr^{90} and 2000 $\mu\mu$c/day for Sr^{89}. I estimate that after extended exposure of the average critical members of the population these values would correspond to dose equivalents of 0.5, 3, 0.7 and 0.3 rem/yr, respectively; or they correspond to multiplication factors of 1/60, 1/10, 1/40 and 1/100; this represents a deviation by a factor of three from the factor of 1/30, suggested by the ICRP (see last column of Table 2).

Internal Dose

The values of annual dose equivalent permitted to occupational workers, as listed in the second column of Table 1, have been used by the NCRP (*10*) and the ICRP (*18*) in calculating values of maximum permissible body burden, q, and maximum permissible concentration (MPC) in air, water, and food for more than 250 radionuclides. These calculations are based on the standard man (*18, 19*). The limiting or smallest value of MPC is the concentration of the radionuclide in air, water, or food that will deliver the permissible annual dose equivalent, R_{50}, to the critical body organ after 50 years of occupational exposure (see column 2, Table 1, for values of R_{50}). The critical body organ is the one that, after receiving radionuclide, is responsible for the greatest body damage. This is usually the organ with the highest concentration of the radionuclide. Many simplifications are made in the calculations of MPC values because of the limited accuracy of available biological data. For example, it is assumed in these calculations that the radionuclide is eliminated exponentially from the body organ with an ef-

Table 2. Levels of radiation dosages recommended by ICRP and factors applied to occupational dose equivalent values. These values are in addition to doses from medical and from background exposure. The unit of dose equivalent (*13*) is the rem defined as: (No. of rem) = (No. of rad) × (RBE) × n.

Dose to gonads or total body		Dose to most other organs	
Dose rate*	Factor†	Dose rate‡	Factor†
	A: Occupational worker		
3 rem/13 wk § 12 rem/yr or 5 rem/yr (av) §	1	4 rem/13 wk or 15 rem/yr §	1
	B_A: Worker in vicinity		
1.5 rem/yr	3/10 of 40 hr MPC	1.5 rem/yr	1/10 of 40 hr MPC
	B_B: Visit area occasionally		
1.5 rem/yr	3/10 of 40 hr MPC	1.5 rem/yr	1/10 of 40 hr MPC
	B_C: Live in vicinity ‖		
0.5 rem/yr §	1/10 of 168 hr MPC	1.5 rem/yr	1/10 of 168 hr MPC
	C: Whole population ¶		
0.5 rem/yr § or 5 rem** (av) to age 30 or 0.17 rem/yr §, ** (av) 0.05 rem/yr (av)	1/100†† of 168 hr MPC	1.5 rem/yr or 15 rem (av) to age 30 or 0.5 rem/yr (av)	1/30†† of 168 hr MPC

* All dose rates are maximum levels except in the cases where average values are indicated. Values in column 1 apply also to blood forming organs and to certain mixtures of radionuclides. They apply to eyes only in the case of high LET radiation (α, protons, Neutrons). In case of low LET radiation (α, β^+, β^-, x-, γ, and e^-), the values given in column 3 should be used for the eyes. † This factor when applied to internal exposure must be reduced if there is concurrent external exposure. ‡ Values in column 3 are multiplied by 2 when applied to skin, thyroid, or bone; they are multiplied by 5 when applied to hands, forearms, feet, or ankles. § These values have been recommended also by the FRC (*8*). ‖ At the 1962 ICRP meeting in Stockholm, group B_C was included as a part of group C. ¶ The average values for whole population are "suggested" and not "recommended" by ICRP. The Ad Hoc Committee of NCRP (*17*) has "suggested" an average rate in the neighborhood of background (or 0.1 rem/yr) but this has not been confirmed by NCRP. ** These values should be multiplied by 0.3 to obtain the portion of dose suggested for internal sources. †† These fractions are to be applied specifically to the values of permissible occupational dose. They may be applied to MPC if appropriate corrections are made.

fective half life, T, expressed by the equation

$$T = T_r T_b/(T_r + T_b)$$

in which T_r is the radioactive half life and T_b is the biological half life. The maximum permissible concentration (MPC), for continuous occupational exposure is given by

$$\mathrm{MPC} = \frac{cqf_2}{Tf\ (1 - e^{-0.693t/T})} \qquad (2)$$

in which c is 10^{-7} for inhalation or 9.2×10^{-4} for ingestion of water or food when MPC is the number of microcuries per milliliter for occupational exposure 40 hours per week, q is the body burden in microcuries, qf_2 is the organ burden in microcuries, f is the fraction taken into the body that arrives in the critical organ, T is the effective half life in days, and t is the period of exposure in days which is taken as 50 years in these calculations. This body burden is expressed by

$$q = \frac{5.4 \times 10^{-5} mR}{f_2 \Sigma E(\mathrm{RBE})n} \qquad (3)$$

in which m is the mass of the critical body organ in grams, R is the permissible dose equivalent in rems per year (see column 2, Table 1), E is the effective energy per disintegration of the radionuclide, RBE of the radiation is 1 for x, β^-, β^+, e^-; 10 for α; and 20 for atom recoils, n is 1 except when the radionuclide considered is deposited in the bone and even then it is 1 for x- and γ-radiation, and for all radiation when the parent of the chain is radium; otherwise, n is 5 for radionuclides deposited in the bone. Actually, in the case of bone-seeking radionuclides the value of body burden, q, is obtained by a comparison with Ra^{226} in which case the value of q is 0.1 μc. The value of R in Eq. 3 corresponding to a q of 0.1 for Ra^{226} is 30 rem/yr and this value of R is used in Eq. 3 in finding the value of q for all other bone-seeking radionuclides unless they emit only x- or γ-radiation. If the bone-seeking radionuclide emits only x- or γ-radiation, the value of q is obtained from Eq. 3 by making R equal to 15 rem/yr. As stated earlier in this article, the value of 0.1 μc of Ra^{226} for q was adopted by an Advisory Committee of the National Bureau of Standards in 1941 (*4*).

The way in which the radionuclides build up in the critical body organs when an occupational worker is exposed at the MPC over a long period

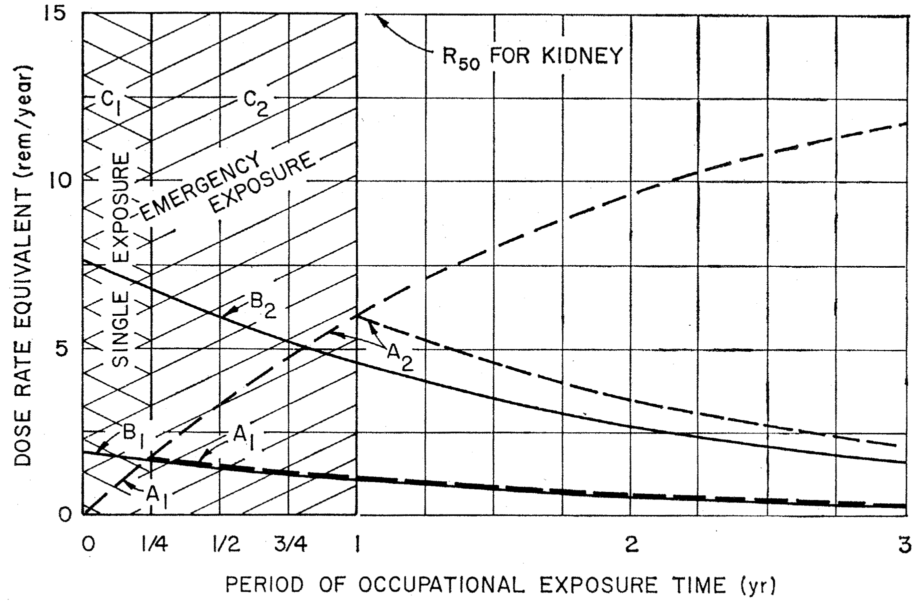

Fig. 3. Equivalent dose rate and integrated dose for single exposure and for emergency exposure at the maximum permissible occupational exposure levels. The curves are for Pb^{210} in which case the kidney is the critical body organ.

of time is shown in Fig. 1. In the case of a short-lived radionuclide such as I^{131}, saturation at the limiting dose rate R_{50} equal to 30 rem/yr to the thyroid is reached for practical purposes in a few months, while in the case of Sr^{90} equilibrium is not reached even after 50 years of occupational exposure at the MPC when R reaches R_{50} equal to 30 rem/yr to the bone.

Since the accumulated dose is proportional to the area,

$$\int_0^{50} R dt,$$

under these dose rate curves, the claim is sometimes made that the values of MPC for long lived radionuclides are too conservative in that as $T \rightarrow \infty$

$$\int_0^{50} R dt \rightarrow 50\ R_{50}/2$$

instead of 50 R_{50}. This limiting case is illustrated by the dashed curve in Fig. 2 for a hypothetical radionuclide in which $T \rightarrow \infty$. In practice, however, this is not the case because very few persons will be occupationally exposed for 50 years. The areas under the dashed curves with discontinuous slope at τ equals 5 yr correspond to the integrated doses to the bone as a result of five year exposures to Ce^{144}, Sr^{90}, and Pu^{239} at the MPC values for occupational exposure. The values of

$$\int_0^{50} R dt,$$

for these 5-year exposures (τ equals 5 yr) are equal to 150 rem for Ce^{144}, 147.6 rem for Sr^{90}, 143.1 rem for Pu^{239}, and 142.5 rem for the hypothetical radionuclide. In this example of a 5-year exposure the "safety factor" of two has disappeared even for the hypothetical radionuclide (for which $T \rightarrow \infty$).

Many internal exposures of occupational workers are not at a constant MPC value but are single high exposures or erratic exposures. The ICRP has provided a simple rule for determining whether or not such exposures are permissible. Figure 3 shows the application of the single exposure rule in the case of Pb^{210} where the kidney is the critical body organ. The rule specifies that during a quarter (13 weeks) an occupational worker may take into his body in any pattern of intake an amount of the radionuclide corresponding to occupational exposure at the MPC for 1/4 of a year. The 50-year integrated dose from such a single intake in the case of Pb^{210} corresponds to the area under curve A_1 (dashed lines) of Fig. 3. Thus, the area under curve A_1 is equal to the area under the permissible single intake curve B_1 (solid line) and this area, in turn, is equal to the area of the rectangle C_1 (ordinate R_{50} is 15, abscissa 1/4).

The planned emergency exposure rule is the same as the single exposure rule except in this case, and, as shown in Fig. 3, the permissible dose corresponds to that which would be received from the intake of a radionuclide at the occupational MPC for one year. In summary, the maximum permissible single dose equivalent corresponds to the area under curve A_1 = area under curve B_1 = area of rectangle $C_1 = R_{50}/4$ and the maximum permissible planned emergency dose equivalent corresponds to the area under curve A_2 = area under curve B_2 = area of rectangle $C_2 = R_{50}$. Even in the case of the actinide elements such as Pu for which T_b is 200 yr, the area under curve A_2 is 99.1 percent of R_{50}. Values of R_{50} for the various body organs are listed in column 2, Table 1.

The expression "planned emergency exposure" always elicits heated discussions and controversy, but it is a useful guide to exposure and signifies the dose allowed for the ordinary emergency situations, for example, exposures to the emergency crew that shuts down the facility after a reactor accident or exposures to those not engaged directly in rescue operations. Obviously, no such upper limit can be set for the dose permitted to those engaged in rescue operations. Certainly, in order to rescue casualties, it may be necessary at times for a few individuals to be exposed to 100 or 200 rem or more.

For the case of normal single external exposure, the recommended values are listed in the first column of Table 1. In addition, the ICRP lists 12 rem as the limit for planned emergency external exposure to the total body, and the values in the second column of this table can be applied for planned emergency external exposure to single organs. Both the ICRP and the NCRP list 25 rem as a once-in-a-lifetime accidental exposure to the total body and the NCRP lists 125 rem as a once-in-a-lifetime accidental exposure to the hands, forearms, feet and ankles.

Future Developments

Without making rash predictions of future changes in the MPE values, it is safe to state that any significant changes in the basic dose values listed in Table 1 in the next few years are unlikely. It is certain, however, that as more reliable information becomes available, there will be many changes and adjustments in the MPC values designed to limit the dose rate to the critical body organs of the occupational worker to not more than R_{50} rem/yr (values of R_{50} given in the second column of Table 1). This applies also to refinements in the MPC values suggested for the general population. In this instance, specific values of MPC or of maximum permissible daily intake (equals the MPC for water × the daily water intake by the critical population group) must be determined for the radionuclides of interest with reference to the critical population groups, which, in most cases, can be expected to be young children or developing fetuses. When the ICRP first suggested factors (as shown in Table 2) which could be multiplied by the values of R_{50} to obtain suitable limiting dose rates for the general population, it cautioned that these same factors might be applied to the occupational MPC values in obtaining provisional MPC values for the general population but they indicated that this should be done only as a first step. This word of caution was given because the rate of intake, radiation sensitivity, size of critical organ, biological half life, and so forth, in the case of the critical members of the population might deviate considerably from these characteristics for the standard man (*18*); thus further reductions would become necessary in obtaining MPC values applicable to the general population.

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