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RELATIVE BIOLOGICAL HAZARDS OF RADIATIONS EXPECTED IN HOMOGENEOUS REACTORS TBR AND HPR

E. D. Arnold
A. T. Gresky

OAK RIDGE NATIONAL LABORATORY
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UNION CARBIDE NUCLEAR COMPANY
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CHEMICAL TECHNOLOGY DIVISION

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0.0 ABSTRACT

An evaluation of the relative health hazards of radioisotopes produced in nuclear reactors is reported. The most important hazards were indicated to be I^{131}, the Sr^{90}-Y^{90} chain, the Ce^{144}-Pr^{144} chain, Sr^{89}, the Ba^{140}-La^{140} chain, Y^{91}, the Zr^{95}-Nb^{95} chain, Pr^{143}, La^{140}, and Pa^{233}. The most critical body organs affected by air-borne contamination are the thyroid gland, the bone marrow, the lungs, and the gastro-intestinal tract. Where possible, continuous daily removal of gaseous and solid fission products from the reactor environment can be shown to permit very significant reductions in the total hazards. Homogeneous reactors, such as the Thermal Breeder Reactor and the Homogeneous Plutonium Producer Reactor, specifically studied in this report, are designed with daily removal cycles and may be considered potentially safer than heterogeneous reactors.

1.0 SUMMARY

The most significant internal biological hazards from continuous exposure at biological equilibrium in the thorium-U^{233} breeder reactors were indicated to be, in the following general order, La^{140}, I^{131}, Ba^{140}-La^{140} chain, Pa^{233}, Ce^{144}-Pr^{144} chain, Y^{91}, Mn^{56}, Xe^{135}, and Pr^{143}. For the plutonium producer reactors the important hazards would be the same with the exception that Pa^{233} would not be included. The body organs primarily affected would be the bone, the thyroid gland, and the gastro-intestinal tract.

The most significant internal biological hazards from short-term emergency exposure resulting from a thorium-U^{233} breeder reactor failure were indicated to be Pa^{233}, I^{131}, Ba^{140}-La^{140} chain, Ce^{144}-Pr^{144} chain, Sr^{89}, Nb^{95}, La^{140}, Pr^{143}, Mn^{56}, and Mo^{99}. The Pa^{233} would account for about 65% of the hazard attributable to the thorium blanket. In the case of the plutonium producer reactors, hazards would be the same with the exception of Pa^{233}. The body organs primarily affected immediately after short-term exposure would be the lungs, the thyroid, and the gastrointestinal tract.

The most significant biological hazards in either type of reactor from the standpoint of maximum total integrated dose following large exposure are indicated to be, in the following general order, Sr^{90}-Y^{90} chain, I^{131}, Ce^{144}-Pr^{144} chain, Sr^{89}, Ba^{140}-La^{140} chain, Y^{91}, Zr^{95}-Nb^{95}, and Pr^{143}. Pa^{233} would add considerable hazard in an accident involving the thorium blanket and would rank fifth. All isotopes, with the exception of I^{131}, would cause extensive damage to the bone over extended periods of time.

The three types of exposure were studied from the standpoint of probabilities of occurrence, range and extent of probable incident, and biological damage. The continuous-exposure studies were concerned with maximum permissible activity levels associated with the routine operation of the reactor or chemical plant. The single-exposure studies were concerned with maximum permissible major-emergency activity levels. The total-integrated-dose studies were concerned with activities of lethal or damaging proportions, large body burdens, and wide area dispersions. The combined results of these studies revealed the following fission products as the most hazardous:

(1) I^{131}: present at a high activity level; would be at radioactive equilibrium in reactor and activity would not increase with increase in reactor operating cycle; concentrates in thyroid gland; both immediate and total integrated damage to thyroid would be great; short half-life would result in large decrease in hazard several weeks after incident.

(2) Sr^{90}-Y^{90}: bone seeker; immediate damage would not be great with short processing periods because of low activity level in reactor, but long processing periods ($>$ 80 days) would increase hazard proportionally; would result in considerable total integrated damage to bone because of long effective half-life.

(3) Ce^{144}-Pr^{144}: bone seeker; would cause considerable immediate damage to lungs and extensive integrated damage to bone; has moderately long effective half-life.

(4) Sr^{89}: bone seeker; present at a high activity level and increases only slightly with longer operating cycle; immediate damage to lungs would be high and extensive integrated damage would be caused to bone; has moderately long effective half-life.

(5) Ba^{140}-La^{140}: bone seeker; present at a high activity level; near radioactive equilibrium in reactor; chain would cause extensive immediate damage to lungs as well as long-term damage to bone; has short half-life and would become less important several weeks after an incident.

(6) Y^{91}: bone seeker; present at a high activity level and would increase only slightly with longer operating cycle; would cause extensive immediate damage to lungs and long-term damage to bone; has a moderately long effective half-life.

(7) Zr^{95}-Nb^{95}: present at moderately high activity level which would increase slightly with a longer operating cycle; would cause considerable immediate damage to lungs; could cause considerable long-term damage to bone although classed as only minor bone seeker; has moderately long effective half-life.

(8) Pr^{143}: present at high activity level which would be near radioactive equilibrium in reactor; would cause considerable immediate damage to lungs; could cause considerable long-term damage to bone although classed as a minor bone seeker with short effective half-life.

(9) La^{140}: daughter of Ba^{140} and is present at a very high activity level near reactor saturation; would decay with a 12.5-day half-life

when in equilibrium with Ba^{140} or 40-hr half-life if separated from Ba^{140}; would cause 95% of total expected immediate damage to gastrointestinal tract.

The most important fission product hazards with the percentage of the total hazard contributed by each member for these three situations are listed in Table 1-1. Alpha emitters and other fission products make up the balance.

The investigations of hazards resulting from a single exposure in an 80-day reactor operating cycle was considered most significant from reactor and chemical plant maintenance philosophy. The effects of decay in reducing contamination before maintenance is undertaken were studied for this case (see Tables 3-3, 5-1, and Figs. 5-1 and 5-2.)

For short-term high-level exposure, I^{131} would constitute approximately one-third of the total fission product hazard and would damage primarily the thyroid gland. Alkaline earths and rare earths would constitute one-half to two-thirds of the total hazard, with primary damage to the lungs and gastrointestinal tract. (These groups are known to exert primary damage to the bone marrow in cases of long-term exposures.) Cs^{137} would account for approximately 3 per cent of the total hazard and would exert its primary influence in the lungs.

The alpha emitters would account for less than 0.5 per cent of the total hazard. Their order of importance as hazards were: U^{233}, Pu^{239}, natural thorium, and natural uranium. Damage from these materials in short-term high-level exposure would involve, in order, the lungs, the bone, and the kidney. Long-term damage would be exerted primarily in the bone.

Among the corrosion products that would be present in solution reactors, it appeared that Mn^{56}, Fe^{59} and Fe^{55} would be the important hazards. The 2.6-hr manganese isotope would exert considerable damage to the gastrointestinal tract if the exposure occurred during the first few hours after shutdown of the reactor, accounting for approximately 1 per cent of the gastrointestinal tract damage. The iron isotopes would primarily affect the blood.

Table 1-1

Contribution of Major Fission Product

Isotopes to Total Fission Product Hazard

Fission Product	Percentage of Total Fission Product Hazard		
	Based on Continuous Exposure and Biological Equilibrium	Based on Single Permissible Exposure to 1-year Dose in 1 day (80-day Reactor Operating Cycle)	Based on Relative Probability of Obtaining Maximum Total Integrated Dose (80-day Reactor Operating Cycle)
I^{131}	26.9	36.4	20.3
Sr^{90}-Y^{90}	1.2	0.5	22.2
Ce^{144}-Pr^{144}	4.6	13.6	17.7
Sr^{89}	1.9	7.0	16.5
Ba^{140}-La^{140}	11.1	16.0	11.5
Y^{91}	4.6	13.4	8.7
Zr^{95}-Nb^{95}	0.6	3.5	1.2
Pr^{143}	2.1	3.0	0.8
La^{140}	33.7	3.2	0.3
Total	86.7	96.6	99.2

Results of the analysis of the hazards due to the rare gas fission products are not clear-cut for the case of short-term exposures because certain fundamental data were not available. In the case of long-term exposures, the effects of Xe^{135} and Xe^{133} would account for about 4 per cent of the total hazard, exerting their primary damage to the total body.

A hypothetical example to illustrate the order of damage which could be expected from an uncontrolled leak of 0.5% of the reactor volume and an assumed 0.5% of the available I^{131} follows: If this material was thoroughly dispersed in a volume equivalent to a building approximately 150 by 180 by 100 ft, breathing of this air for 10 sec would provide an individual with a total dose to the thyroid of 1200 rem during a period of 8 days following exposure and a total dose of 2340 rem for the year following exposure. Exposure of the total body to the gamma constituents in such air would result in an external dose rate to the body of 42 rem/hr. Such an example does not take into consideration additional effects due to rare gases or other fission products which might escape with the iodine.

Removal of the rare earth and alkaline earth fission products from the reactor fuels, as proposed, would contribute very significantly to the reduction of the biological hazards, especially from the Homogeneous Plutonium Producer Reactor. The health hazards justify considerable study of I^{131} removal. In the case of the Homogeneous Thermal Breeder Reactor, Pa^{233} recovery or handling constitutes an additional problem for study.

2.0 INTRODUCTION

The purpose of this study was to determine the potential radiation hazards associated with the operation of homogeneous power reactors. A knowledge of the relative hazards of individual fission products and other pertinent radioisotopes was needed to evaluate the worth of various tentative proposals for chemical processing of the core and blanket solutions of the Thermal Breeder and Homogeneous Plutonium Producer Reactors.

Since the reactor fuel system will involve high-pressure liquid and gas media containing extremely high concentrations of radioactivity, minor disaster effects such as small leaks into the air or into the heat exchanger systems may involve serious danger to personnel and to the public. Therefore the optimum chemical process, based on radiation safety considerations, will be that which is most effective in the continuous removal of the critically hazardous fission elements, such as iodine, rare earths, and strontium.

A study of biological hazards must contain inherent uncertainties because of basic limitations of absolute measurement in the realm of radiobiology and safety engineering. However, reasonable approximations of the relative health hazards of individual iosotopes can be mathematically determined. Assuming air dispersion of portions of radioactive solutions from the reactors, operating at known power levels and on defined chemical processing cycles for fission product removal, the relative importance of given isotopes as contributors to radiation dosage of exposed persons can be evaluated. Recently available data (see Appendix, Sec. 7) on radiation dose limits and critical parameters of health physics were used in conjunction with the currently conceived nuclear characteristics of the TBR and HPR proposals to establish such relative values.

This report indicates the relative importance and the orders of magnitude of significant health hazards associated with given radioisotopes calculated on the basis of (1) concentration of the substance in air and its resulting effect on an individual exposed (a) continuously to a low level of activity and (b) briefly (assumed to be 1 day) to a high level of activity, and

(2) the total integrated dose to a critical organ. Calculations indicate the maximum possible effects for a given condition and do not necessarily reflect actual conditions. For example, in the case of a leak through a very small hole, solid fission products might remain in the reactor and danger to the exposed operator would be less than calculated.

The relative hazards listed in the tables of this study are general for any reactor condition. The quantities of radioactive material and the magnitude of the radiation hazard resulting from an accident of any size may be found by multiplying the relative hazard by a constant determined by actual reactor conditions.

The scope of this study does not permit analysis of those factors in reactor and chemical plant design which will certainly be utilized to increase the personnel and public safety of a nuclear power plant. The intent was to define basically the unique health importance of certain radioisotopes in relation to a wide variety and number of less important isotopes which may have either relatively short half-lives or low biological effectiveness in the human body. However, certain revelations of the study tend to illustrate the unusual order of dangerous activity levels which will be attained in power producers of the 500-Mw range. It appears that a new consciousness must be established in the area of solution chemistry and processing because inadvertent exposures involving small volumes of reactor solutions can approach lethal proportions. No compromise will be possible in the remote operation and analytical control of hydroclone or solvent extraction processes.

3.0 BASIC ASSUMPTIONS AND METHODS

It was assumed that any accident, either minor or catastrophic, would result in air contamination (water was not considered in this report) and that damage to the body organs would result from inhalation of the activity-laden air. The relative hazard of a given isotope can be based on either (1) its concentration in the air or (2) the total dose that reaches a critical organ and the amount of damage it does to the organ.

There are several ways in which relative biological hazards may be expressed. The first involves the probability that a minor equipment leak or accident will result in air contamination to the extent of the maximum permissible concentration for long periods of exposure at biological equilibrium. The second involves the probability that an accident will contaminate the air to the extent that a day's intake of radioisotopes will result in a 15.7-rem* (maximum permissible year's dose) total integrated dose during the year following exposure. Such an activity level can be tolerated only for minor emergency maintenance, and then the workers should not be permitted to handle radioactive systems for the year following exposure. The third involves the probability that the intake of radioisotopes will result in a maximum integrated dose to the critical organ. For comparison purposes using this method, the period of integration was assumed long compared to the effective half-life.

1. The relative hazard of an isotope based on its concentration in air is found from the expression

$$\text{Relative hazard} = \frac{\text{amount of activity leaving reactor}}{\text{allowable activity level in air}} .$$

The amount of activity leaving the reactor is a function of the power level, the fission yield, the length of the chemical processing period or irradiation time, the decay constant of the particular isotope, and the probability (and size) of a leak, i.e., $\phi \Sigma_f y(1 - e^{-\lambda t_r})$ x leak probability, where ϕ is the thermal flux in neutrons per square centimeter per second, Σ_f is the total fission cross-section per unit quantity of U^{235} in square centimeters, y is the fission yield in atoms of fission product per atom of U^{235} fissioned, λ is the radioactive decay constant, and t_r is the irradiation time in days. The allowable activity level in air is determined by the radioactive characteristics of the radioisotopes and the biological characteristics of the elements in the body. The leak probability is related to the mechanical design of the reactor and associated components but cannot be determined here.

It can be assumed to be the same for all radioisotopes, and it was therefore not incorporated in the mathematical expressions. In this report the relative hazards of the radioisotopes based on the allowable air contamination level were determined under conditions of (a) continuous exposure to air contaminated at a low activity level and (b) a single exposure to air contaminated at a high activity level (so that a 15.7-rem dose is received in 1 year) with radioactive materials formed in a 1.44-day and an 80-day irradiation period. The results are given in Tables 3-1, 3-2, and 3-3.

2. The relative hazard based on total integrated dose to the critical organ is found from the expression

$$\text{Relative hazard} = \frac{\text{amount of activity absorbed by the critical organ x time}}{\text{allowable activity burden in critical organ}}.$$

The amount of activity absorbed by the critical organ depends on the amount of activity leaving the reactor and the probability of its reaching the organ, which in turn is a function of the biological processes and the chemistry of the given organ. The length of time a given activity remains in the critical organ depends on the sum of the rates of radioactive decay and biological elimination; this sum determines the effective half-life of the given isotope. The allowable amount of an active material in a critical organ is determined by the radioactive characteristics of the radioisotope and the biological characteristics of the element in the organ. A reactor irradiation period of 80 days was chosen for the one case in which the realtive hazard based on the total dose from the inhaled radioisotope was determined.

A comparison of radioisotopes on the basis of total integrated dose to the critical organ is given in Table 3-4. Such a comparison indicates the probability that any given radioisotope will cause the maximum damage to the critical organ but does not consider the length of time required for the exposed person to obtain the total dose since the period of integration was considered long compared to the effective half-life. However, Sr^{90}-Y^{90}, which would cause the greatest total integrated damage, is the only major fission product hazard that has an effective half-life (7.7 years) greater

than 180 days. Although Sr^{90}-Y^{90} would contribute a smaller initial dose rate and a lower integrated dose over the first year after intake than I^{131} or Ce^{144}-Pr^{144}, its activity within the critical organ (bone) will have been decreased by only 8.6% after 1 year. The irradiation of the critical organ by this product will continue although the other radioisotopes will have been reduced in level several-fold owing to a combination of radioactive decay and biological elimination.

As an illustration, the magnitude of the I^{131} hazard resulting from an arbitrarily selected small leak was determined. Iodine was chosen because it is the most important single fission product from an internal biological standpoint and because there is a possibility that iodine will leave the core solution as free iodine vapor along with the steam from any loop leak. The other radioisotopes of iodine — I^{132}, I^{133}, I^{135} — would increase the total iodine hazard immediately after an accident by a factor of approximately 2 but the hazard from these would decrease more rapidly than the hazard from I^{131}.

The calculations given show a method for converting the relative hazards listed in Tables 3-1, 3-2, and 3-3 to the actual magnitude of the radiation hazard resulting from a leak. The physical quantity most easily established is curies of activity for a given isotope per gram of U^{235} divided by the MPC or MPSEV (see pp. 20, 21 for definitions) which expresses the volume (cubic meters) of air necessary to dilute that quantity of a given isotope to the concentration corresponding to the maximum permissible single exposure value or the maximum permissible concentration.

The recommended permissible total body burden and maximum permissible concentration in air and water of some seventy radioisotopes under conditions of continuous exposure have been published. [1,2] In obtaining these values it was assumed that an equilibrium condition is reached if a radioisotope is taken into the body continuously over a period of time that is long compared to the effective half-life of the radioisotope in the critical organ. The critical organ is defined as that organ of the body receiving the radioisotope that results in the greatest damage to the body.

Table 3-1

Comparison of Important Fission and Corrosion Products Based on Biological Hazard for Continuous Exposure to Air Contaminated at Low Activity Level

Isotope	Radioactive Half-life (days)	Yield, Y (%)	Critical Organ	Maximum Permissible Conc. in Air ($\mu c/cc$)	Relative Hazard, $Y/(T_{1/2} \cdot MPC)$
La^{140}	1.67	6.6	G.I. tract	5×10^{-8}	7.82×10^{7}
I^{131}	8	3.0	Thyroid	6×10^{-9}	6.25×10^{7}
Ba^{140}-La^{140}	12.8	6.6	Bone	2×10^{-8}	2.58×10^{7}
Pa^{233}(s)	27.4	132.0[a]	Bone	2×10^{-7}	2.4×10^{7}
Ce^{144}-Pr^{144}	287	5.9	Bone	2×10^{-9}	1.07×10^{7}
Y^{91}	61	5.5	Bone	9×10^{-9}	1.07×10^{7}
Mn^{56}	0.108	0.56	G.I. tract	5×10^{-7}	1.04×10^{7}
Xe^{135}	0.38	6.6	Total body	2×10^{-6}	8.68×10^{6}
Pr^{143}	13.8	6.1	G.I. tract	9×10^{-8}	4.91×10^{6}
Rh^{105}	1.52	1.4	G.I. tract	2×10^{-7}	4.6×10^{6}
Mo^{99}	2.85	6.2	G.I. tract	5×10^{-7}	4.35×10^{6}
Sr^{89}	53	4.6	Bone	2×10^{-8}	4.33×10^{6}
Sr^{90}-Y^{90}	7.3×10^{3}	4.9	Bone	2×10^{-10}	3.3×10^{6}
Ce^{141}	33	5.7	Bone	9.6×10^{-8}	1.8×10^{6}
Zr^{95}-Nb^{95}	65 and 35	6.7	G.I. tract	7×10^{-8}	1.48×10^{6}
Nb^{95}	35	6.7	Bone	2×10^{-7}	9.57×10^{5}
Te^{129}	32	0.62	G.I. tract	10^{-7}	4.85×10^{5}
Xe^{133}	5.27	6.8	Total body	4×10^{-6}	3.22×10^{5}
Ru^{106}-Rh^{106}	365	0.45	G.I. tract	2×10^{-8}	6.16×10^{4}
As^{76}	1.12	2.5×10^{-3}	G.I. tract	4×10^{-8}	5.58×10^{4}
Pm^{147}	1.46×10^{3}	2.6	Bone	4×10^{-8}	4.45×10^{4}
Ag^{111}	7.5	1.5×10^{-2}	G.I. tract	8×10^{-8}	2.5×10^{4}
Eu^{154}	1.97×10^{3}	8.5×10^{-2}	Bone	2×10^{-9}	2.16×10^{4}
Te^{127}	90.4	0.11	G.I. tract	10^{-7}	1.22×10^{4}

[a] Based on 20% breeding gain.

Table 3-1, Continued

Isotope	Radioactive Half-life (days)	Yield, Y (%)	Critical Organ	Maximum Permissible Conc. in Air ($\mu c/cc$)	Relative Hazard, $Y/(T_{1/2} \cdot MPC)$
Fe^{59}	46.3	4.0×10^{-3}	Blood	2×10^{-8}	4.33×10^{3}
Cs^{137}-Ba^{137}	1.2×10^{4}	6.6	Muscle(or G.I.)	2×10^{-7}	2.75×10^{3}
Cr^{51}	26.5	0.281	G.I. tract	4×10^{-6}	2.64×10^{3}
Ga^{72}	0.59	10^{-4}	G.I. tract	10^{-7}	1.7×10^{3}
Sm^{151}	3.6×10^{5}	0.5	Bone	3×10^{-9}	4.63×10^{2}
Sn^{113}	112	0.014	G.I. tract	3×10^{-7}	4.16×10^{2}
Fe^{55}	1.06×10^{3}	0.197	Blood	7×10^{-7}	2.66×10^{2}
Cu^{64}	0.54	10^{-5}	G.I. tract	9×10^{-7}	20
Ga^{71}	11.4	10^{-4}	G.I. tract	3×10^{-6}	3.0
Zn^{65}	250	10^{-5}	G.I. tract	4×10^{-7}	1.0×10^{-1}
Th^{234}-Pa^{234}	24.1	---	Bone	10^{-8}	---
Pu^{239}(s)	8.8×10^{6}	100	Bone	2×10^{-12}	5.68×10^{6}
Pu^{239}(i)	8.8×10^{6}	100	Lungs	2×10^{-12}	5.68×10^{6}
U^{233} (s)	5.9×10^{7}	5180	Bone	3×10^{-11}	2.92×10^{6}
U^{233}(i)	5.9×10^{7}	5180	Lungs	3×10^{-11}	2.92×10^{6}
U, natural(s)	1.64×10^{12}	2.15×10^{6}	Kidneys	3×10^{-11}	4.36×10^{4}
U, natural(i)	1.64×10^{12}	2.15×10^{6}	Lungs	3×10^{-11}	4.36×10^{4}
Th, natural	5×10^{12}	4.85×10^{6}	Bone	3×10^{-11}	3.24×10^{4}
U^{235}(s)	2.59×10^{11}	5180	Bone	3×10^{-11}	6.67×10^{2}
U^{235}(i)	2.59×10^{11}	5180	Lungs	3×10^{-11}	6.67×10^{2}

Table 3-2

Comparison of Important Fission and Corrosion Products

Based on Biological Hazard for 15.7-rem Dose Quantity of Radioisotope

in 1 day Following Accident, 1.44-day Operating Cycle

Isotope	Radioactive Half-life (days)	Yield, Y (%)	Critical Organ	Concentration in Air to Give 15.7-rem Dose in 1 day (μc/cc)	Relative Hazard, $Y/(T_{1/2} \cdot MPSEV)$
I^{131}	8	3.0	Thyroid	8×10^{-7}	4.69×10^{5}
La^{140}	1.67	6.6	G.I. tract	2×10^{-5}	1.97×10^{5}
Ba^{140}-La^{140}	12.8	6.6	Lungs	4×10^{-6}	1.29×10^{5}
Mo^{99}	2.85	6.2	Lungs	6×10^{-4}	3.63×10^{4}
Nb^{95}	35	6.7	Lungs	6×10^{-6}	3.2×10^{4}
Ce^{144}-Pr^{144}	275	6.9	Lungs, bone	8×10^{-7}	2.68×10^{4}
Mn^{56}	0.108	0.56	G.I. tract	2×10^{-4}	2.59×10^{4}
Y^{91}	57	5.5	Lungs, bone	4×10^{-6}	2.42×10^{4}
Pr^{143}	13.8	6.1	Lungs	2×10^{-5}	2.21×10^{4}
Sr^{89}	53	4.6	Bone	2×10^{-6}	4.34×10^{4}
Rh^{105}	1.52	1.4	G.I. tract	6×10^{-5}	1.54×10^{4}
Te^{129}	32	0.62	Lungs	2×10^{-6}	9.7×10^{3}
Ce^{141}	33	5.7	Bone, lungs	3.5×10^{-5}	5.0×10^{3}
Sr^{90}-Y^{90}	7.3×10^{3}	4.9	Bone	2×10^{-7}	3.3×10^{3}
Ru^{106}-Rh^{106}	365	0.45	Lungs	7×10^{-7}	1.76×10^{3}
Cs^{137}-Ba^{137}	1.2×10^{4}	6.6	Lungs	10^{-6}	550
Te^{127}	90.4	0.11	Lungs	5×10^{-6}	244
Pm^{147}	1.46×10^{3}	2.6	Lungs	10^{-5}	178
As^{76}	1.12	2.5×10^{-3}	G.I. tract	2×10^{-5}	112
Ag^{111}	7.5	1.5×10^{-2}	G.I. tract	3×10^{-5}	67
Eu^{154}	1.97×10^{3}	8.5×10^{-2}	Lungs	10^{-6}	43
Fe^{59}	46.3	4.0×10^{-3}	Blood	3×10^{-6}	29

Table 3-2, Continued

Isotope	Radioactive Half-life (days)	Yield, Y (%)	Critical Organ	Concentration in Air to Give 15.7-rem Dose in 1 day (μc/cc)	Relative Hazard, $Y/(T_{1/2} \cdot MPSEV)$
Cr^{51}	26.5	0.281	Lungs	4×10^{-4}	26
Sn^{113}	112	0.014	Lungs	5×10^{-6}	25
Ga^{72}	0.59	10^{-4}	G.I. tract	4×10^{-5}	4
Fe^{55}	1.06×10^{3}	0.197	Blood	10^{-4}	1.9
Sm^{151}	3.6×10^{5}	0.5	Lungs	4×10^{-5}	3.5×10^{-2}
Cu^{64}	0.54	10^{-5}	Lungs	8×10^{-4}	2.3×10^{-2}
Zn^{65}	250	10^{-5}	Lungs	3×10^{-6}	1.3×10^{-2}
Ge^{71}	11.4	10^{-4}	Lungs	9×10^{-4}	9.8×10^{-3}
Ni^{59}	9.1×10^{7}	0.675	Lungs	2×10^{-5}	3.68×10^{-4}
U, natural(s)	1.64×10^{12}	2.15×10^{6}	Kidneys	10^{-8}	131
U, natural(i)	1.64×10^{12}	2.15×10^{6}	Lungs	9×10^{-9}	146
U^{233}(s)	5.9×10^{7}	5180	Bone	4×10^{-8}	2200
U^{233}(i)	5.9×10^{7}	5180	Lungs	2×10^{-8}	4390
U^{235}(s)	2.59×10^{11}	5180	Bone	4×10^{-8}	0.5
U^{235}(i)	2.59×10^{11}	5180	Lungs	2×10^{-8}	1
Pu^{239}(s)	8.8×10^{6}	100	Bone	6×10^{-9}	1900
Pu^{239}(i)	8.8×10^{6}	100	Lungs, bone	9×10^{-9}, 8×10^{-10}	1260, 1.4×10^{4}
Th, natural	5×10^{12}	7.17×10^{6}	Lungs	2×10^{-9}	717
Pa^{233} (s)	27.4	132	Lungs	7.1×10^{-6}	6.8×10^{5}

Table 3-3

Comparison of Important Fission and Corrosion Products for Eighty Day Operating Cycle, Based on Biological Hazard for 1 Year's Permissible Dose in 1 Day of Exposure

Isotope	Half-life (days)	Yield, Y (%)	Critical Organ	Conc. in Air to Give 15.7-rem Dose in 1 day (μc/cc)	Relative Hazard at Saturation Y/MPSEV	Saturation Factor, F[a] at 80 days	YF/MPSEV	Decay Factor, f_{2d}	Relative Hazard after 2 days Cooling, YFf_{2d}/MPSEV	Decay Factor, f_{10d}	Relative Hazard after 10 days Cooling, YFf_{10d}/MPSEV	Decay Factor, f_{30d}	Relative Hazard after 30 days Cooling YFf_{30d}/MPSEV
Pa^{233}[b]	27.4	26.4[c]	Lungs	$7.1x10^{-6}$	$3.2x10^{6}$	1.0	$3.2x10^{6}$	0.95	$3.04x10^{6}$	0.775	$2.48x10^{6}$	0.47	$1.50x10^{6}$
I^{131}	8	3.0	Thyroid	$8x10^{-7}$	$3.75x10^{6}$	1.0	$3.75x10^{6}$	0.841	$3.15x10^{6}$	0.420	$1.57x10^{6}$	0.074	$2.77x10^{5}$
Ba^{140}-La^{140}	12.8	6.6	Lungs	$4x10^{-6}$	$1.65x10^{6}$	1.0	$1.65x10^{6}$	0.90	$1.48x10^{6}$	0.57	$9.4x10^{5}$	0.19	$3.14x10^{5}$
Ce^{144}-Pr^{144}	275	5.9	Lungs	$8x10^{-7}$	$7.37x10^{6}$	0.19	$1.4x10^{6}$	1.0	$1.4x10^{6}$	0.98	$1.37x10^{6}$	0.92	$1.29x10^{6}$
Sr^{89}	53	4.6	Bone	$2x10^{-6}$	$2.3x10^{6}$	0.63	$1.45x10^{6}$	0.95	$1.38x10^{6}$	0.86	$1.25x10^{6}$	0.68	$9.86x10^{5}$
Y^{91}	57	5.5	Lungs	$4x10^{-6}$	$1.38x10^{6}$	0.62	$8.55x10^{5}$	0.95	$8.12x10^{5}$	0.95	$8.12x10^{5}$	0.88	$7.52x10^{5}$
Nb^{95}	35	6.7	Lungs	$6x10^{-6}$	$1.12x10^{6}$	0.325	$3.64x10^{5}$	1.05	$3.82x10^{5}$	1.2	$4.37x10^{5}$	1.3	$4.73x10^{5}$
La^{140}	1.67	6.6	G.I.	$2x10^{-5}$	$3.3x10^{5}$	1.0	$3.3x10^{5}$	0.95	$3.14x10^{5}$	0.65	$2.14x10^{5}$	0.22	$7.25x10^{4}$
Pr^{143}	13.8	6.1	Lungs	$2x10^{-5}$	$3.05x10^{5}$	1.0	$3.05x10^{5}$	0.90	$2.75x10^{5}$	0.60	$1.83x10^{5}$	0.22	$6.7x10^{4}$
Mn^{56}	0.108	0.56	G.I.	$2x10^{-4}$	$2.8x10^{3}$	1.0	$2.8x10^{3}$	0	0	0	0	0	0
Mo^{99}	2.85	6.2	Lungs	$6x10^{-5}$	$1.03x10^{5}$	1.0	$1.03x10^{5}$	0.80	$8.25x10^{4}$	0.09	$9.26x10^{3}$	0.001	$1.03x10^{2}$
Te^{129}	32	0.62	Lungs	$2x10^{-6}$	$3.1x10^{5}$	0.82	$2.54x10^{5}$	0.95	$2.41x10^{5}$	0.81	$2.06x10^{5}$	0.52	$1.32x10^{5}$
Sr^{90}-Y^{90}	$9.1x10^{3}$	4.9	Bone	$2x10^{-7}$	$2.45x10^{7}$	0.0061	$1.50x10^{5}$	1.0	$1.50x10^{5}$	1.0	$1.50x10^{5}$	1.0	$1.50x10^{5}$
Ce^{141}	33	5.7	Lungs, bone	$3.5x10^{-5}$	$1.63x10^{5}$	0.82	$1.34x10^{5}$	0.96	$1.28x10^{5}$	0.81	$1.08x10^{5}$	0.53	$7.10x10^{4}$
Ru^{106}-Rh^{106}	365	0.45	Lungs	$7x10^{-7}$	$6.43x10^{5}$	0.15	$9.65x10^{4}$	1.0	$9.65x10^{4}$	0.98	$9.45x10^{4}$	0.95	$9.17x10^{4}$
Cs^{137}-Ba^{137}	$1.2x10^{4}$	6.6	Lungs	10^{-6}	$6.6x10^{0}$	0.0047	$3.1x10^{4}$	1.0	$3.1x10^{4}$	1.0	$3.1x10^{4}$	1.0	$3.1x10^{4}$
Rh^{105}	1.52	1.4	G.I.	$6x10^{-5}$	$2.34x10^{4}$	1.0	$2.34x10^{4}$	0.4	$9.35x10^{3}$	0.01	$2.34x10^{2}$	0	0
Te^{127}	90.4	0.11	Lungs	$5x10^{-6}$	$2.2x10^{4}$	0.465	$1.02x10^{4}$	0.99	$1.01x10^{4}$	0.92	$9.37x10^{3}$	0.80	$8.15x10^{3}$
Pm^{147}	$1.46x10^{3}$	2.6	Lungs	10^{-5}	$2.6x10^{5}$	0.038	$9.8x10^{3}$	1.0	$9.8x10^{3}$	1.0	$9.8x10^{3}$	1.0	$9.8x10^{3}$
Eu^{154}	$1.97x10^{3}$	$8.5x10^{-2}$	Lungs	10^{-6}	$8.5x10^{4}$	0.028	$3.38x10^{3}$	1.0	$3.38x10^{3}$	1.0	$3.38x10^{3}$	1.0	$3.38x10^{3}$
Sn^{113}	112	0.014	Lungs	$5x10^{-6}$	$2.8x10^{3}$	0.39	$1.1x10^{3}$	0.99	$1.09x10^{3}$	0.93	$1.02x10^{3}$	0.82	$9.0x10^{2}$
Fe^{59}	46.3	$4.0x10^{-3}$	Blood	$3x10^{-6}$	$1.33x10^{3}$	0.71	$9.35x10^{2}$	0.97	907	0.86	804	0.64	600
Cr^{51}	26.5	0.281	Lungs	$4x10^{-4}$	$7.0x10^{2}$	0.87	$6.1x10^{2}$	0.95	580	0.77	470	0.46	280
Ag^{111}	7.5	$1.5x10^{-2}$	G.I.	$3x10^{-5}$	$5x10^{2}$	1.0	$5x10^{2}$	0.82	410	0.40	200	0.07	35
As^{76}	1.12	$2.5x10^{-3}$	G.I.	$2x10^{-5}$	$1.25x10^{2}$	1.0	$1.25x10^{2}$	0.29	36.2	0.002	0.25	0	0
Fe^{55}	$1.06x10^{3}$	0.197	Blood	10^{-4}	$19.7x10^{2}$	0.048	9.45	1.0	94.5	1.0	94.5	1.0	94.5
Ga^{76}	0.59	10^{-4}	G.I.	$4x10^{-5}$	2.5	1.0	2.5	0.1	0.25	0	0	0	0
Sm^{151}	$3.6x10^{5}$	0.5	Lungs	$4x10^{-5}$	$1.25x10^{4}$	0.000154	1.93	1.0	1.93	1.0	1.93	1.0	1.93
Zn^{65}	250	10^{-5}	Lungs	$3x10^{-6}$	3.33	0.20	$6.7x10^{-1}$	0.99	0.66	0.97	0.65	0.92	0.62
Ge^{71}	11.4	10^{-4}	Lungs	$9x10^{-4}$	$1.1x10^{-1}$	1.0	$1.1x10^{-1}$	0.89	$9.9x10^{-2}$	0.54	$5.9x10^{-2}$	0.16	$1.76x10^{-2}$
Ni^{59}	$9.1x10^{7}$	0.675	Lungs	$2x10^{-5}$	$3.37x10^{4}$	$6.1x10^{7}$	$2.06x10^{-2}$	1.0	$2.06x10^{-2}$	1.0	$2.06x10^{-2}$	1.0	$2.06x10^{-2}$
Cu^{64}	0.54	10^{-5}	Lungs	$8x10^{-4}$	$1.25x10^{-2}$	1.0	$1.25x10^{-2}$	0.1	$1.25x10^{-3}$	0	0	0	0
U,natural (s)	$1.64x10^{12}$	$7.94x10^{-7}$	Kidneys	10^{-8}	79	d	79	1.0	79	1.0	79	1.0	79
U,natural (i)	$1.64x10^{12}$	$7.94x10^{-7}$	Lungs	$9x10^{-9}$	88	d	88	1.0	88	1.0	88	1.0	88
U^{233} (s)	$5.9x10^{7}$	$6.7x10^{-4}$	Bone	$4x10^{-8}$	$1.7x10^{4}$	d	$1.7x10^{4}$	1.0	$1.7x10^{4}$	1.0	$1.7x10^{4}$	1.0	$1.7x10^{4}$
U^{233} (i)	$5.9x10^{7}$	$6.7x10^{-4}$	Lungs	$2x10^{-8}$	$3.4x10^{4}$[e]	d	$3.4x10^{4}$[e]	1.0	$3.4x10^{4}$[e]	1.0	$3.4x10^{4}$[e]	1.0	$3.4x10^{4}$[e]
U^{235} (s)	$2.59x10^{11}$	$1.53x10^{-7}$	Bone	$4x10^{-8}$	3.85	d	3.85	1.0	3.85	1.0	3.85	1.0	3.85
U^{235} (i)	$2.59x10^{11}$	$1.53x10^{-7}$	Lungs	$2x10^{-8}$	7.7	d	7.7	1.0	7.7	1.0	7.7	1.0	7.7
Pu^{239}(s)	$8.8x10^{6}$	$6.65x10^{-6}$	Bone	$6x10^{-9}$	1665	d	1665	1.0	1665	1.0	1665	1.0	1665
Pu^{239}(i)	$8.8x10^{6}$	$6.65x10^{-6}$	Lungs	$9x10^{-9}$	740	d	740	1.0	740	1.0	740	1.0	740
			Bone	$8x10^{-10}$	8400	d	8400	1.0	8400	1.0	8400	1.0	8400
Th, natural	$5x10^{12}$	$8.67x10^{-7}$	Lungs	$2x10^{-9}$	434	d	434	1.0	434	1.0	434	1.0	434

[a] Saturation factor = $1-e^{-\lambda t_r}$, where λ is the radioactive decay constant and t_r is the irradiation time in days.

[b] Only for THR blanket.

[c] Based on 20% breeding gain and 20% of Mass 233 as Pa^{233}.

[d] Not used because calculations were based on reactor conditions.

[e] 2.2×10^{5} for blanket.

Table 3-4

Comparison of Important Fission and Corrosion Products Based on Biological Hazard for Maximum Integrated Dose Given to Critical Organ as a Result of a Single Major Incident, 80-day Operating Cycle

Isotope	Yield, Y (%)	Effective Half-life (days)	Saturation Factor, F^a	YF	$f_a YFT/f_2 q^b$
Sr^{90}-Y^{90}	4.9	2.7×10^3	0.0076	0.0372	31.7
I^{131}	3.0	7.7	1.0	3.0	29.0
Ce^{144}-Pr^{144}	5.9	180	0.19	1.12	25.3
Sr^{89}	4.6	52	0.63	2.898	23.7
Ba^{140}-La^{140}	6.6	12	1.0	6.6	16.5
Y^{91}	5.5	51	0.62	3.41	12.5
Ce^{141}	5.7	30	0.82	4.67	2.2
Zr^{95}-Nb^{95}	6.7	48	0.57	3.82	1.70
Pr^{143}	6.1	11	1.0	6.1	1.18
La^{140}	6.6	1.6	1.0	6.6	0.50
Te^{129}	0.62	10	0.82	0.508	0.365
Nb^{95}	6.7	21	0.325	2.177	0.31
Xe^{133}	6.8	5.27	1.0	6.8	0.112
Ru^{106}-Rh^{106}	0.45	19	0.15	0.0675	8.0×10^{-2}
Pm^{147}	2.6	140	0.038	0.099	7.1×10^{-2}
Rh^{105}	1.4	1.5	1.0	1.4	5.7×10^{-2}
Eu^{154}	8.5×10^{-2}	1.2	0.028	2.38×10^{-3}	3.6×10^{-2}
Xe^{135}	6.6	0.56	1.0	6.6	2.5×10^{-2}

[a] Saturation factor = $1-e^{-\lambda t_r}$, where λ = the radioactive decay constant and t_r = the irradiation time in days.

[b] f_a = fraction of radioisotope inhaled which is retained in critical organ; f_2 = fraction of that in total body which is retained in critical organ; q = maximum permissible body burden.

Table 3-4, Continued

Isotope	Yield, Y(%)	Effective Half-life, T (days)	Saturation Factor, F(a)	YF	$f_a YFT/f_2 q$ (b)
Te^{127}	0.11	13	0.465	0.512	1.65×10^{-2}
Mn^{56}	0.56	0.104	1.0	0.56	6.2×10^{-3}
Fe^{59}	4.0×10^{-3}	27	0.71	2.84×10^{-3}	5.9×10^{-3}
Cs^{137}-Ba^{137}	6.6	17	0.0047	0.031	4.2×10^{-3}
Sm^{151}	0.5	3.9×10^{4}	1.54×10^{-4}	7.7×10^{-5}	2.6×10^{-3}
Fe^{55}	0.197	61	0.048	9.5×10^{-3}	6.1×10^{-4}
Mo^{99}	6.2	2.8	1.0	6.2	4×10^{-4}
Sn^{113}	0.014	44	0.39	5.46×10^{-3}	2.7×10^{-4}
As^{76}	2.5×10^{-3}	1.09	1.0	2.5×10^{-3}	6.2×10^{-5}
Ag^{111}	1.5×10^{-2}	2.1	1.0	1.5×10^{-2}	1.6×10^{-5}
Ga^{72}	10^{-4}	0.59	1.0	10^{-4}	2.4×10^{-6}
Ge^{71}	10^{-4}	3.9	1.0	10^{-4}	7.7×10^{-8}
Cu^{64}	10^{-5}	0.53	1.0	10^{-5}	7.1×10^{-8}
Zn^{65}	10^{-5}	21	0.20	2×10^{-6}	3.5×10^{-8}
Ni^{59}	0.675	8	6.1×10^{-7}	4.1×10^{-7}	8.1×10^{-10}
Th, natural	8.67×10^{-7}	4.3×10^{4}	1.0	8.67×10^{-7}	0.91
Th^{234}+Pa^{234}	5×10^{-3}	24.1	1.0	5×10^{-3}	1.46×10^{-2}
Pa^{233} (s)	26.4	25.6	1.0	26.4	5.8
U, natural(s)	7.94×10^{-7}	30	1.0	7.94×10^{-7}	7.32×10^{-4}
U, natural(i)	7.94×10^{-7}	120	1.0	7.94×10^{-7}	1.15×10^{-3}
U^{233}(s)	6.7×10^{-4}	300	1.0	6.7×10^{-4}	0.30
U^{233}(i)	6.7×10^{-4}	120	1.0	6.7×10^{-4}	0.60
Pu^{239}(s)	6.65×10^{-6}	4.3×10^{4}	1.0	6.65×10^{-6}	1.71
Pu^{239}(i)	6.65×10^{-6}	360	1.0	6.65×10^{-6}	0.014

Since many persons are working with radioactive material under conditions such that an accident could lead to a large single exposure, similar tables for such cases would be useful, but no official maximum permissible single exposure values have been published. Unofficial values have been published[3] of the concentrations of various isotopes in air which give, in a single day, dose quantities of 0.043, 0.3, and 15.7 rem.* For the case based on large single exposures the 15.7-rem dose quantity was the only one considered because it was assumed that an operator would receive more than a day's or a week's permissible dose on the day following an accident. Three critical organs are listed for each radioisotope but there is usually one critical organ for each isotope for which the maximum permissible single exposure value is much less than for the other two. With most radioisotopes the critical organ is the lungs for single exposure values. The breathing rate was taken as 2×10^7 cc of air per day, and therefore the maximum permissible intake is 2×10^7 x maximum permissible single exposure value ($\mu c/cc$). For purposes of comparison, the critical organ for each individual isotope was chosen as that organ which limited the maximum permissible single exposure value ($\mu c/cc$) to a minimum, whether the radioisotope was insoluble or soluble.

4.0 CALCULATIONS

4.1 Calculation of Fission Product Hazards

Since fission products are formed in atomic units and maximum permissible quantities of any radioactive substance are recorded in disintegration units, it is necessary to report relative biological hazards as a combination of the two. At radioactive equilibrium the number of atoms, N_{eq}, of fission products is given by

$$N_{eq} = \frac{\phi \Sigma_f y}{\lambda} \qquad (1)$$

* The maximum permissible dose in 1 day, 1 week, and 1 year, respectively.

where ϕ = thermal flux, $n/cm^2/sec$;

Σ_f = total fission corss-section per unit quantity of U^{235}, cm^2;

y = fission yield, or number of atoms of fission product per atom of U^{235} fissioning;

λ = radioactive decay constant.

(The denominator of the right-hand member of Eq. 1 should be $\lambda + \phi\sigma$, but the capture cross-section, σ, of the nuclide is neglected.)

A curie of activity is defined as that quantity of a given isotope which has a disintegration rate of 3.7×10^{10} d/sec. Therefore the activity at reactor equilibrium, C_{eq}, or curies at equilibrium, is

$$C_{eq} = \frac{\phi \Sigma_f y}{\lambda} \times \frac{\lambda}{3.7 \times 10^{10}} = \frac{\phi \Sigma_f y}{3.7 \times 10^{10}}. \qquad (2)$$

For the case of the reactor having operated for sufficient time that all materials are at radioactive equilibrium, the relative hazard, $R.H._E$, can be determined from the relation

$$R.H._E = \frac{\text{equilibrium curies of fission product}}{\text{conc. of fission products to give a known dose}}.$$

The relative hazard under conditions of continuous exposure, $R.H._{lE}$, is found from

$$R.H._{lE} = \frac{\phi \Sigma_f y}{3.7 \times 10^{10}} \Big/ MPC = \frac{A_l Y}{MPC} \qquad (3)$$

where Y = % fission yield = 100y;

$$A_l = \frac{\phi \Sigma_f (1/100)}{3.7 \times 10^{10}};$$

MPC = maximum permissible concentration in air ($\mu c/cc$) for long-period exposures resulting in a dose rate of 0.3 rem/week to tissues.

The relative hazard for a single exposure, $R.H._{2E}$, as in the case of emergency maintenance, is found from

$$R.H._{2E} = \frac{\phi \Sigma_f y}{3.7 \times 10^{10}} \Big/ MPSEV = \frac{A_1 Y}{MPSEV} \tag{4}$$

where MPSEV = maximum permissible single-exposure value (μc/cc) to give an integrated dose of 15.7 rem during the year following a 1-day intake of radioactive material of this concentration.

When the reactor irradiation time is specified, the activity, C_t, for an irradiation time in days, t_r, can be found from

$$C_t = C_{eq} F \tag{5}$$

where $F = 1 - e^{-\lambda t_r}$ = the fraction of reactor equilibrium at time t_r. The relative hazard for the continuous exposure case, $R.H._1$, can be found from

$$R.H._1 = \frac{\phi \Sigma_f F y}{3.7 \times 10^{10}} \Big/ MPC = \frac{A_1 YF}{MPC} \tag{6}$$

and the relative hazard for the emergency case, $R.H._2$, can be found from

$$R.H._2 = A_1 YF/MPSEV. \tag{7}$$

To convert YF to $\frac{\text{curies}}{\text{g } U^{235}}$ or $\frac{R.H.*}{A_1}$ to $\frac{\text{curies/g } U^{235}}{\text{MPC or MPSEV}}$, multiply by the term $\frac{\phi \Sigma_f \times 10^{-2}}{3.7 \times 10^{10}}$. The physical significance of the term $\frac{\text{curies/g } U^{235}}{\text{MPC or MPSEV}}$ is that it gives the volume of air (cubic meters) necessary to dilute the quantity of a given fission product associated with a gram of U^{235} to the concentration corresponding to the MPC or MPSEV. Flushing the building with a larger quantity of air would lower the concentration below these limits.

*The terms YF/MPC and YF/MPSEV are used in the tables to express the relative hazard because the constant A_1 (assumed to be unity for sake of convenience) depends on reactor conditions.

However, for the case of short-time-cycle reactor operation, when only the very short-half-life fission products are in equilibrium, the expression for the longer lived fission product concentrations is

$$N = \frac{\phi \Sigma_f y}{\lambda} (1 - e^{-\lambda t_r}) \tag{8}$$

where N = number of atoms of fission product at time t_r. For short periods, of the order of a few days, if linear buildup of all fission products is assumed, Eq. 8 simplifies to

$$N = \phi \Sigma_f y t_r . \tag{9}$$

The activity in curies of the given fission product is expressed by

$$C_{t_r} = \frac{N\lambda}{3.7 \times 10^{10}} = \frac{\phi \Sigma_f y t_r \lambda}{3.7 \times 10^{10}} \tag{10}$$

and thus, for short irradiation periods, the relative hazard with continuous exposure at biological equilibrium, $R.H._{1s}$, is found from

$$R.H._{1s} = \frac{\dfrac{\phi \Sigma_f y t_r \lambda}{3.7 \times 10^{10}}}{MPC} = \frac{A_1 Y t_r \lambda}{MPC} \tag{11}$$

and for single, or emergency, exposures,

$$R.H._{2s} = \frac{A_1 Y t_r \lambda}{MPSEV} . \tag{12}$$

However, $\lambda = 0.693/T_{1/2}$, where $T_{1/2}$ is the radiological half-life, and for the purpose of simplicity all fission products listed in Tables 3-1 and 3-2 are compared on an effective irradiation time of $t_r = 1/0.693 = 1.44$ days in order to use the following expressions:

$$R.H._{1s} = \frac{A_1 Y}{T_{1/2} \cdot MPC} \tag{13}$$

or $Y/T_{1/2} \cdot MPC$ in Table 3-1, where A_1 is assumed to be unity;

$$R.H._{2s} = \frac{A_1 Y}{T_{1/2} \cdot MPSEV} \tag{14}$$

or $Y/T_{1/2} \cdot MPSEV$ in Table 3-2 where A_1 is assumed to be unity. In order to convert $Y/T_{1/2}$ to curies/g U^{235}, multiply by

$$\frac{\phi \Sigma_f \times 10^{-2}}{3.7 \times 10^{10}} \times 0.693\ t_r$$

The relative hazard of radioisotopes based on the maximum acute body burden and total integrated dose is obtained from the total dose relation[3]

$$D = \frac{73.9 f_a I_o T \Sigma E(RBE)N}{m} (1 - e^{-0.693t/T}) \tag{15}$$

and the approximation

$$q = \frac{8.4 \times 10^{-4} m}{f_2 \Sigma E(RBE)N} \tag{16}$$

where D = total dose of ionizing radiation delivered to the critical organ in t days, rem;

f_a = fraction of inhaled radioisotope which is retained in critical organ;

I_o = total amount (μc) of radioisotope inhaled or ingested in a single exposure;

T = effective half-life, days;

E = effective energy, in Mev, delivered to the critical organ per disintegration of the radioisotope (see Sec. 7.4);

RBE = relative biological effectiveness of the radiation relative to 200-kv X radiation (see Sec. 7.4);

N = a nonuniform distribution factor (see Sec. 7.2);

m = mass of critical organ, g;

q = maximum permissible body burden, μc;

f_2 = fraction of radioisotope in total body which is retained in critical organ.

Values for q and $\Sigma E(RBE)N$ are given in Table 7-5.

If the term $73.9I_o$ is replaced by $A'YF$, where A' is a constant relating neutron flux, fission cross-section, and probability of a reactor quantity of isotope reaching the individual, and F is the fraction of reactor equilibrium, then

$$D = \frac{A'YFTf_a \Sigma E(RBE)N}{m} (1 - e^{-0.693t/T}) \quad (17)$$

$$= A'YFTf_a \frac{8.4 \times 10^{-4}}{qf_2} (1 - e^{-0.693t/T}). \quad (18)$$

Equation 18 may be simplified by assuming $t \gg T$ and combining constants so that all radioisotopes may be compared by the relation

$$R.H._D = \frac{A''YFTf_a}{qf_2} \quad (19)$$

or, for comparison purposes only,

$$R.H._D = \frac{YFTf_a}{qf_2}, \text{ assuming } A'' = 1$$

where $R.H._D$ = relative hazard based on total dose, and

$$A'' = A' \, 8.4 \times 10^{-4} = A_1 \times 8.4 \times 10^{-4} \times 73.9 \times \text{fraction of leaking radioisotope that is inhaled} \times 10^6.$$

4.2 Calculation of Equivalent Yields of Corrosion Products

It is assumed for the purpose of these calculations that the UO_2SO_4-D_2O solution contains corrosion products equivalent to 100 days' operation, the corrosion rate is 1 mil per year, and all products are soluble. The yield, y, which is equal to Y/100, is defined by

$$y = \frac{\text{atoms of irradiation product from corrosion product, } n\gamma \text{ reaction}}{\text{atoms of } U^{235} \text{ fissioned}} \quad (20)$$

$$= \frac{\phi N_{CPI} \sigma_{CPI}}{\phi \Sigma_f} = \frac{N_{CPI} \sigma_{CPI}}{\Sigma_f} \quad (21)$$

where N_{CPI} = number of atoms of corrosion product isotope being irradiated in a given quantity of solution;

σ_{CPI} = capture cross-section of the irradiated corrosion product isotope;

Σ_f = total fission cross-section of U^{235} in the given quantity of solution, cm^2.

An example of such a reaction is

$$Ni^{58} + n \rightarrow Ni^{59} \xrightarrow{9.1 \times 10^7 d, \beta^+} Co^{59}(s).$$

Since only a fraction of a given corrosion product will be present as corrosion product isotope, N_{CPI} will be represented by

$$N_{CPI} = N_{CPZ} \times B_{ZI} \tag{22}$$

where N_{CPZ} = number of atoms of corrosion product with atomic number Z in given volume of solution;

B_{ZI} = relative abundance of corrision product element Z which exists as isotope I;

thus
$$y = \frac{N_{CPZ} B_{ZI} \sigma_{CPI}}{\Sigma_f}. \tag{23}$$

If the average atomic weight of the corrosion product is 56 and W_{CP} = total weight in grams of all corrosion products in a volume of solution containing $\Sigma_f cm^2$ of fission cross-section and M_{CPZ} = mass fraction of all corrosion products with atomic number Z, then

$$N_{CPZ} = \frac{W_{CP}}{56} \times 6.023 \times 10^{23} \times M_{CPZ} \tag{24}$$

and
$$Y = \frac{W_{CP}}{56} \times \frac{6.023 \times 10^{23}}{\Sigma_f} \times M_{CPZ} \times B_{ZI} \sigma_{CPI}. \tag{25}$$

In these calculations the corrosion product concentration was considered to be 3.4 g/liter (100 days of operation at 1 mil/year).

The only activity of any significance resulting from corrosion products is Mn^{56}, but, since Mn^{56} has such a short half-life (2.59 hr), it would be important only immediately after an accident. One day after an accident the Mn^{56} level is down by a factor of 600.

4.3 Calculation of Uranium and Thorium Hazards

The simulated yields for uranium and thorium for the continuous-exposure and short-irradiation-time-at-biological-equilibrium cases were obtained by assuming that the total amount of material would be formed in one day and dividing this number by the U^{235} fissions in one day. In order to get a simulated YF value for uranium, plutonium, and thorium for comparison in the 80-day-operation case, it was necessary to compare these with the fission products on a curie-for-curie basis. The YF value for steady-state quantities is given by

$$YF = \frac{W}{A} \times \frac{6.023 \times 10^{23} \times 100\lambda}{\phi \cdot \Sigma_f} \tag{26}$$

where W = grams of fissile or fertile material in a given volume containing Σ_f cm^2 of fission cross-section;

A = atomic number of material considered;

F = fraction of reactor equilibrium; assumed equal to 1 for purposes of comparison.

When used for the study of the Thermal Breeder and Homogeneous Plutonium Producer Reactors, Eq. 26, when the design parameters ϕ and Σ_f

are substituted, would simplify to

$$YF = W(0.196) \text{ for the Plutonium Producer Reactor;} \quad (27)$$

$$YF = W(0.316) \text{ for the Thermal Breeder Reactor.} \quad (28)$$

4.4 Extent of Fission Product Study

The summation of the yield-saturation term (YF) considered in this study and listed in the tables is 47.4%. Under reactor radioactive equilibrium conditions, in which all chains have come to equilibrium, this term would be 200%. However, there are some chains in which the important isotopes are stable and thus are not important from a radiobiological standpoint, and the parents of some of these stable isotopes are very short-lived and thus would not be important from a radiobiological standpoint except from immediate body contact with a direct burst from a ruptured reactor. Fission products listed in Tables 3-1 through 3-4 were assumed to be removed from the reactor by decay only. No correction for the term $\phi\sigma$ was made since this term is flux-dependent and is not the same for all cases. The total activity of the hazardous HPR fission products after an 80-day reactor irradiation period is approximately 4,700 curies per gram of U^{235}[4]. This would account for 24 total watts of activity per gram of U^{235} after 1 to 2 days' cooling[4]. The hazardous fission products studied would be the only important ones after 1 to 2 days' cooling. The activity immediately after a rupture would be much greater, owing to the very short-lived activities present, than can be accounted for by these fission products; however, there is very little that can be done to prevent or lower the immediate danger from a burst.

4.5 Average Rate of Decay of Fission Products Hazardous to the Three Major Critical Organs

The rate of decay of hazardous fission products was determined for the case of major emergency activity levels and an assumed reactor irradiation period of 80 days. The effective half-life of hazardous fission products was determined in order to estimate a safe waiting time before emergency maintenance may be accomplished following a small burst. Figure 4-1 shows the decay over a 30-day cooling period of the total radioactivity to which each of the three major critical organs is most susceptible. Indications are that the decay of the total radioactivity hazardous to each organ is approximately exponential over the first 30 days of decay and that the following average half-lives can be assigned: lung group, 42.5 days; thyroid, 8 days; gastrointestinal tract, 13 days. It can be seen that considerable time would be required for the activity in the general area of a disaster to decay since the chief hazardous radioisotopes, those that contribute to damage of the lungs, decay with a relatively long half-life.

If the decay period is extended to 100 days, it can be shown that the hazard to the lungs decreases by a factor of 3 over that at discharge, corresponding to an average half-life of 62 days over this 100-day cooling period. The decay of radioisotopes hazardous to the lungs thus is not truly exponential, but exponential decay may be approximated over short periods. The radioactivity contributing as a hazard to the thyroid continues to decay with an 8-day half-life, i.e., I^{131}, and the radioactivity contributing as a hazard to the gastrointestinal tract continues to decay with a 13-day half-life since the major contributor is La^{140} resulting from 12.8-day Ba^{140} decay.

5.0 DISCUSSION

It is not probable that complete removal of or even a 1000-fold reduction in fission product activity would be practical. However, it is feasible to process the core solution on a 1-day cycle to remove

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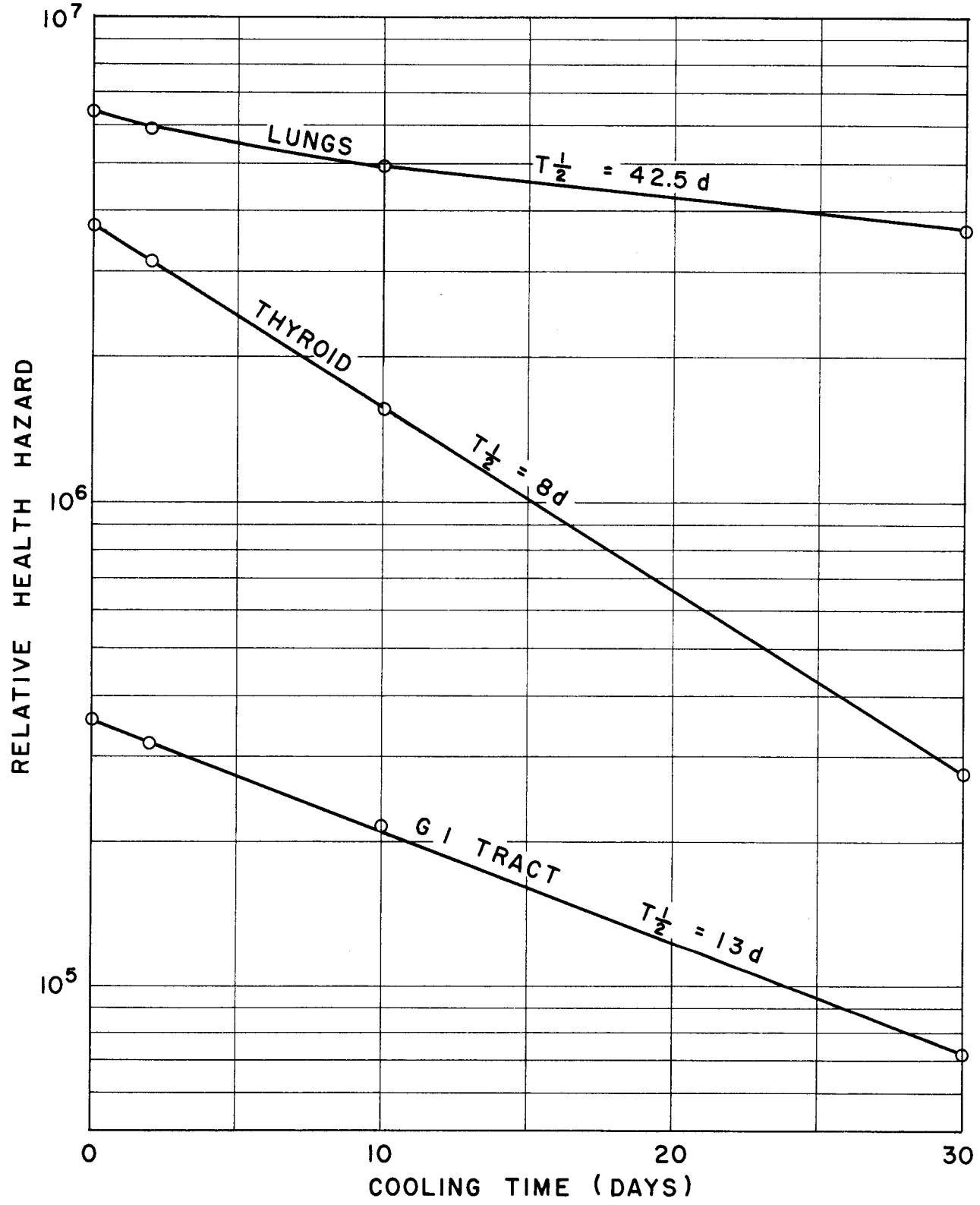

FIGURE 4-1 EFFECT OF COOLING TIME ON DECAY OF RELATIVE HEALTH HAZARD OF THE FISSION PRODUCTS AFFECTING THE THREE MAJOR CRITICAL ORGANS

insoluble rare earths and other fission products as they precipitate. Such a scheme may reduce the hazard contributed by the insolubles by as much as a factor of 30. Although such a reduction will not measurably reduce the immediate hazard of a direct burst to operators in the vicinity of an accident, it will give persons in other areas of the operating building somewhat more time (a minute or so instead of a few seconds) to escape the ensuing lethal cloud. A 30-fold reduction in fission product activity from a large power reactor would also reduce the potential hazard to the surrounding area to that which may be expected from a 10-Mw test reactor.

Solid fission products suspended in fluid reactor systems will probably remain with the bulk of the fluid and very little will leave through a small hole. However, the volatile elements, such as iodine or the rare gases, possibly enriched in the steam phase, could very easily escape with a steam leak and thus become significant hazards. (The very short-half-life rare gases could escape from the reactor and disperse throughout the atmosphere of the reactor building. Decay to their longer half-life daughters could then create a colloidal dispersion in air of the more hazardous fission products.)

A sample problem using I^{131} is given to illustrate the magnitude of a biological hazard. However, similar examples could be given with radioisotopes resulting from the escape of the short-half-life rare gases. The method would be the same as that illustrated except that an equilibrium amount of rare gas would escape, and from this value the quantity of the resulting daughters could be calculated. The extent of internal radiation from these daughters could then be determined, as was done for I^{131}.

5.1 Summation of Relative Hazards Affecting Various Critical Organs

Figures 5-1 and 5-2 are block graphs showing the relative importance of the most hazardous isotopes and the total effect in each critical organ for the cases involving air contamination that were studied. Symbols of the pertinent isotopes are included in the proper blocks, showing the order

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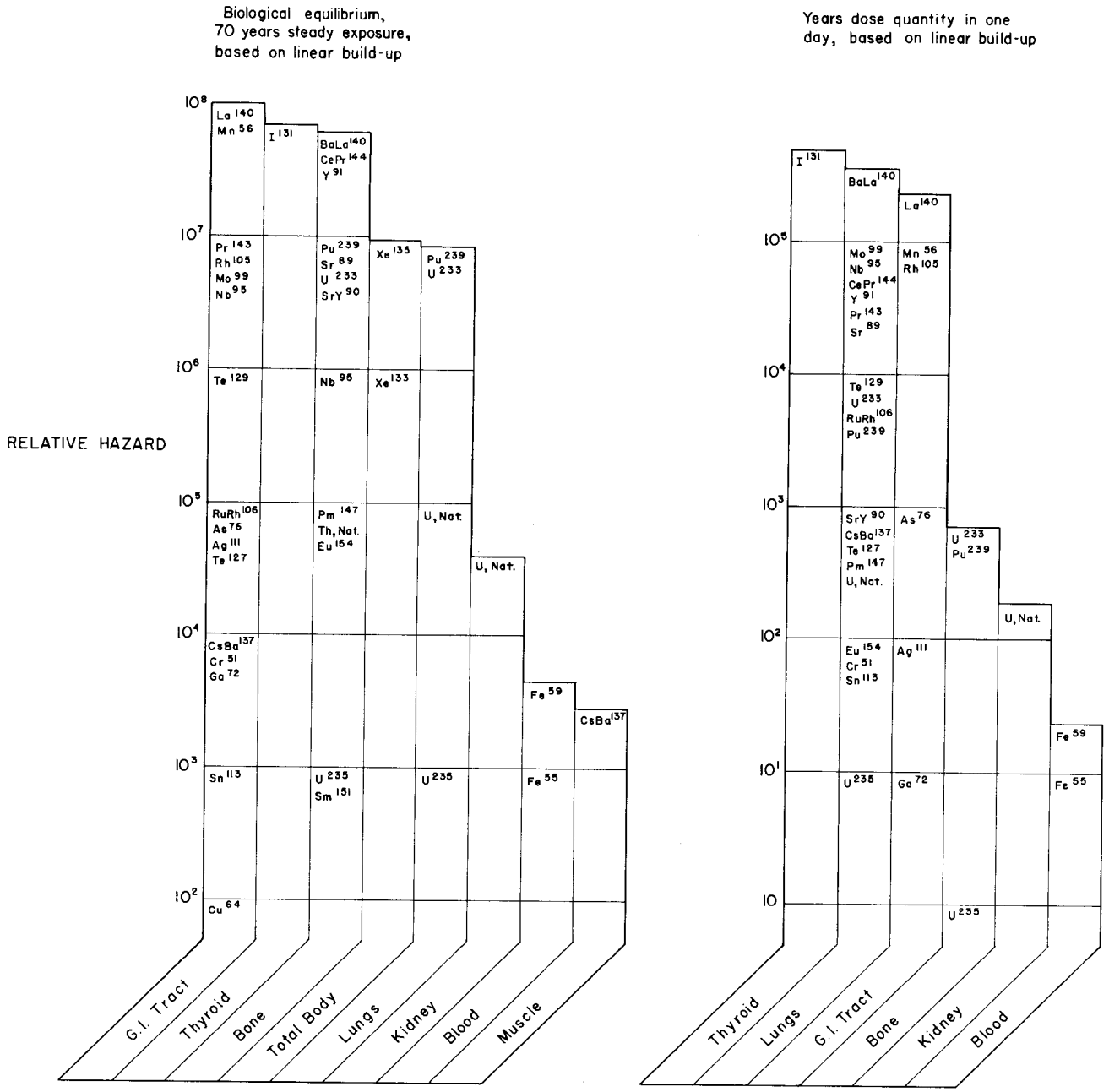

RELATIVE BIOLOGICAL HAZARDS OF ISOTOPES FORMED IN TBR OR HPR

FIG. 5-1

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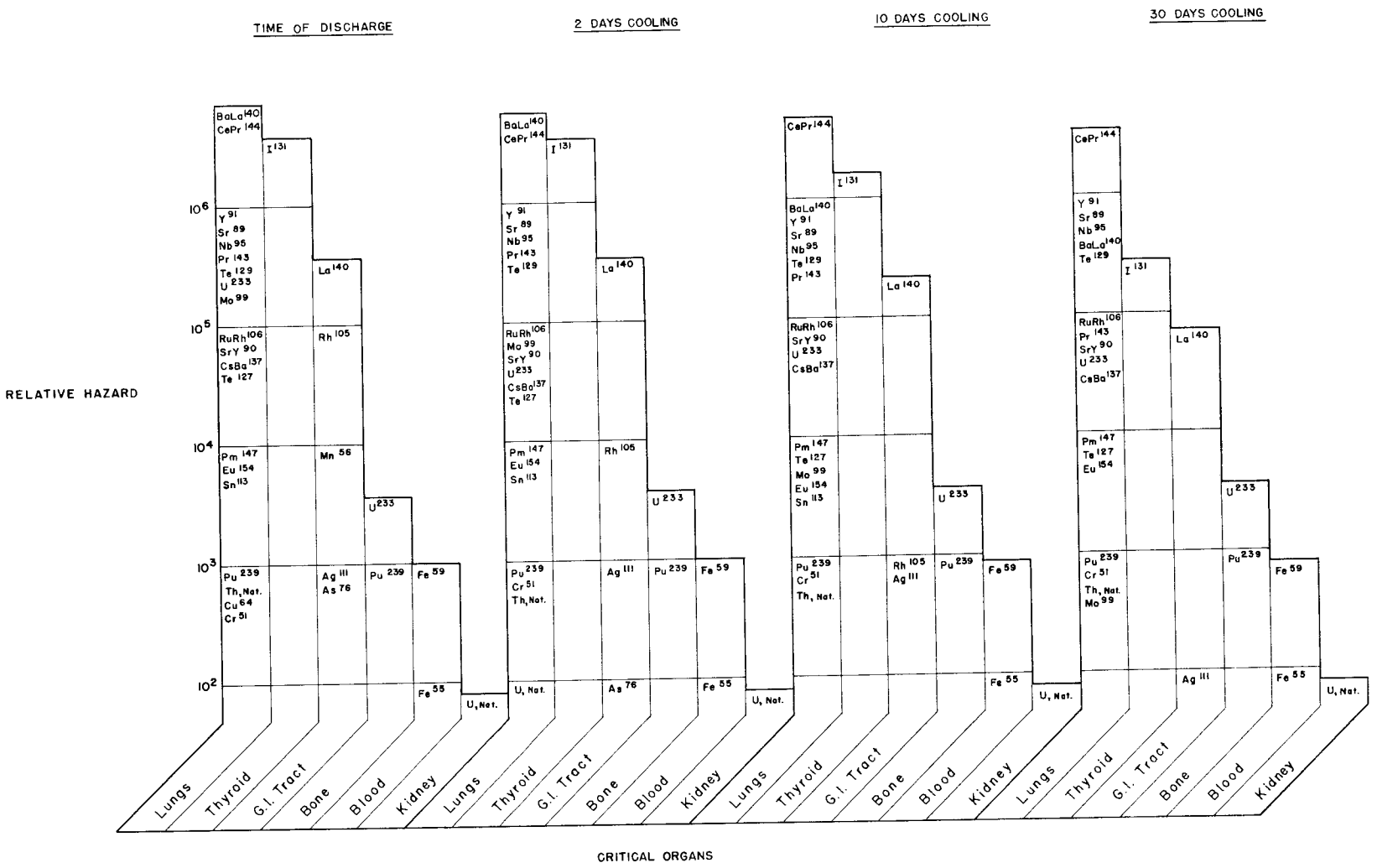
80 DAY OPERATING CYCLE, YEARS DOSE QUANTITY IN ONE DAY EXPOSURE



RELATIVE BIOLOGICAL HAZARDS OF ISOTOPES FORMED IN TBR OR HPR

FIG. 5-2

their contribution to the total hazard. Except Pa^{233}, which is predicted to be the limiting hazard associated with a disaster involving the TBR blanket, it can be readily observed that the primary hazards will include the Ba^{140}-La^{140} chain, the Ce^{144}-Pr^{144} chain, I^{131}, Y^{91}, and Sr^{89}. The generally important critical organs are the lungs, the thyroid, and the gastrointestinal tract.

Continuous exposure at biological equilibrium reveals a considerable importance of the bone and total body as critical organs. The isotopes which contribute primarily to bone damage in this case are the primary contributors to lung damage in all the other cases which represent conditions of a more drastic short-term exposure.

Table 5-1 records the relative biological hazards associated with arbitrary chemical groupings, based on the relative susceptibility to chemical removal from the homogeneous reactor solutions. In this table the hazards are given both as relative numbers and in the form of percentage contribution of the isotopic groups to the overall hazard. The latter permits approximations of safety benefits to be derived by controlling the level of given isotopes in the reactor environment. In the cases which describe conditions of an 80-day operating cycle, it is observed that continuous rare earth and alkaline earth removal would account for a 52 to 72% reduction in the overall biological hazard. Provisions for the continuous removal or control of I^{131} would further decrease the hazard, resulting in an overall reduction of ~80%.

Table 3-4 shows the comparison of the various hazardous isotopes associated with homogeneous reactors based on a maximum total integrated dose to the critical organ from a single exposure. The order of this tabulation is somewhat different than that obtained using maximum permissible single exposure values. However, the essential change produced by considering the fission products this way is to indicate that the Sr^{90}-Y^{90} chain is the most important fission product from total dose standpoint. This result is primarily due to the long effective half-life of Sr^{90}. Although the dose from Sr^{90} delivered during the year following exposure would be

Table 5-1

Relative Biological Hazards of Isotopic Groups Formed in TBR or HPR Based on Air Contamination

Summary of six case studies relating critical organs and relative hazards and percentage contribution attributable to isotopic groups of varying susceptibility to chemical processing

Critical Organ	Isotopes	Continuous Exposure at Biological Equilibrium,[a] Linear Buildup		Single Exposure to High Activity Level, 1.44 Day Operating Cycle, Linear Reactor Buildup; 15.7-rem Dose Quantity in 1 Day's Exposure		Single Exposure to High Activity Level, 80-Day Operating Cycle; at Time of Accident, Cooling of							
						0 days		2 days		10 days		30 days	
		R h x 10^4	%	R.h x 10^4	%	R h. x 10^4	%	R.h. x 10^4	%	R h x 10^4	%	R h x 10^4	%
Thyroid	I^{131}	6250	26 9	47	46 5	375	36.75	315	34.85	157	24.2	27.7	7.06
Lungs	Ba^{140}-La^{140}, Ce^{144}-Pr^{144}, Y^{91}, Pr^{143}, Sr^{90}-Y^{90}, Sr^{89}	---	---	22.5	22 27	520	50.96	470	52.0	391	60.10	280	71.5
	U^{233}, Pu^{239}, natural U, natural Th	865	3.72	0.57	0.56	3.52	0.35	3.52	0.39	3.52	0.54	3.52	0.90
	Nb^{95}, Mo^{99}, Ru^{106}-Rh^{106}	---	---	6.98	6 91	57[b]	5.59	56[b]	6.20	53.8[b]	8.29	56.7[b]	19.45
	Cs^{137}-Ba^{137}	---	---	0.06	0.06	3.1	0.30	3.1	0.34	3.1	0.48	3.1	0.79
	Te^{129}	---	---	0.02	0.02	25.4	2.49	24	2.66	20.6	3.17	13.2	3.37
		865	3.72	30	29.82	609	59.69	557	61.59	472	72.58	357	91.01
Gastro-intestinal tract	La^{140}, Pr^{143}	8290	35.69	20	19.8	33	3.23	31.4	3.48	21.4	3.29	7.25	1.85
	Mn^{56}	1000	4.30	2.6	2.57	0.28	0.03	0.0	0.0	0.0	0.0	0.0	0.0
	Rh^{105}	460	1.98	1.54	1.52	2.34	0.23	0.94	0.1	0.02	0.003	0.0	0.0
		9750	41.97	24	23.89	36	3.49	32	3.58	21	3.293	7	1.85
Bone	U^{233}, Pu^{239}	860	3.70	0.08	0.08	0.37	0.04	0.37	0.04	0.37	0.055	0.37	0.09
	Ba^{140}-La^{140}, Ce^{144}-Pr^{144}, Y^{91}, Sr^{90}-Y^{90}, Sr^{89}	5500	23.67	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
		6360	27.37	0.08	0.08	0.37	0.04	0.37	0.04	0.37	0.055	0.37	0.09
Blood	Fe^{59}, Fe^{55}	0.46	0.002	0.0	0.0	0.1	0.01	0.1	0.01	0.09	0.013	0.07	0.02
Kidney	Natural U	4.36	0.02	0.01	0.01	0.01	0.001	0.01	0.001	0.01	0.002	0.01	0.002
Total		23,230	99.98	101	100.2	1020	99.98	904	100.1	650	100.1	392	100.0

[a]Additional values: total body, Xe^{135}-Xe^{133} = 90.2 x 1 0^4 or 0.37 %; muscle, Cs^{137}-Ba^{137} = 25.9 x 10^4 or 0.11%.

[b]Calculated values for Pa^{233} could raise these values to 1917, 1836, 1494, and 932, respectively, in the case of the TBR blanket.

less than that from some of the others, Sr^{90} would remain in the body to continue to deliver a high dose rate to the bone. The important fission product hazards from the standpoint of total delivered dose would be (1) Sr^{90}-Y^{90} chain, (2) I^{131}, (3) Ce^{144}-Pr^{144} chain, (4) Sr^{89}, (5) Ba^{140}-La^{140}, and (6) Y^{91}. Consideration of Pa^{233} in a TBR blanket would rank the relative hazard of Pa^{233} in the same order of magnitude as Sr^{89}.

The relative hazards of the most important fission products under two different conditions of operation are compared in Table 5-2. These conditions are: 80-day operation of either a heterogeneous or homogeneous reactor without fission product removal, and 80-day operation of a homogeneous reactor with continuous fuel processing on a 1-day cycle for fission product removal. The processing cycle of 80 days was chosen since this period corresponds to the core processing period necessary to maintain an economic fission product poison level if continuous processing is not used as well as the irradiation time expected in many of the future heterogeneous power reactors.

Table 5-2 was obtained by using the previous expressions for the relative hazard and the information listed in the tables of this study (Tables 3-1 through 3-4), or in other words the relative hazards listed in this table are simply the product of the fission yield and buildup factor for the specific irradiation periods divided by the maximum permissible concentrations. The aqueous homogeneous reactors employ dilute uranyl sulfate solution as fuel. At elevated temperatures, many of the fission products, including the rare earths, alkaline earths, zirconium, and niobium, are insoluble, and the possibility exists for removing them continuously by filtration or centrifugation. For the purpose of this study, it was assumed that the fuel solution could be processed on a daily cycle to remove insoluble fission products, and that iodine could also be removed by suitable processing. Since heterogeneous reactors cannot be processed without fuel element dissolution, it is obvious that they are not amenable to continuous processing.

The data in Table 5-2 show that with 80-day reactor operation without continuous processing, I^{131} constitutes approximately one-third of the total fission product hazard and damages primarily the thyroid gland.

Alkaline earths and rare earths constitute one-half to two-thirds of the total hazard, with primary damage to the lungs, bones, and gastro-intestinal tract. With continuous daily processing, the absolute hazards of the fission products are decreased considerably. I^{131} constitutes 50% of the total hazard for a 1-day cycle but the absolute I^{131} hazard has been reduced by a factor of 11.5. The hazard from Ba^{140}-La^{140} may be reduced by a factor of 18.5, Sr^{89} by a factor of 48, Ce^{144}-Pr^{144} by 75, and Sr^{90} by a factor of 80. The total fission product hazard may be reduced by a factor of 18.8 by processing continuously.

Sr^{90}-Y^{90} contributes only a small part of the total dose during the year following exposure. However, this activity remains in the bone for several years and continues to produce damage. This chain, with an effective half-life of 7.7 years, is the only important fission product hazard which has an effective half-life greater than 180 days. For this reason, other fission products will produce 75% or more of their total expected damage during the year following exposure and much less damage thereafter. On the other hand, the activity of Sr^{90}-Y^{90} associated with an 80-day reactor operation will contribute the maximum total over a lifetime following exposure, but at a much lower initial dose rate. Also, it is apparent, because of the long radioactive half-life of Sr^{90}, that this chain will remain active in the soil, water, plant, and animal systems for long periods of time after an accident. For these reasons, continuous processing will not only alleviate the immediate hazard after an accident, but also the potential hazard due to Sr^{90} contamination of the soil or water systems.

5.2 Effects of Activity Resulting from Small Accident

In order to estimate the magnitude of a small accident resulting in loss of less than 1% of the core system solution, the following problem was considered: the effective hazard of a leak of 100 liters of core solution, with the equilibrium concentration of I^{131} contained therein being uniformly distributed throughout the air of a given building. This problem was divided into two parts: (1) the effect of such a leak on the damage to the critical organ and (2) the amounts of total body irradiation from uniformly distributed I^{131} associated with loss of this volume of fuel.

Table 5-2

Biological Hazards Associated with Reactors under Two Operating Conditions and the Hazard Reduction Obtained by Continuous Removal of Fission Products

Isotope	Relative Hazard for 80-day Operation, x 10^{-4}	Relative Hazard for 1-day Processing Cycle, x 10^{-4}	Reduction in Hazard by Continuous Processing
I^{131}	375	32.5	11.5
Ba^{140}-La^{140}	165 (110 to bone)	8.94 (6.0 to bone)	18.5
Sr^{89}	145	3.01	48
Ce^{144}-Pr^{144}	140	1.86	75
Y^{91}	85.5	1.68	51
Nb^{95}	36.4	2.22	16.4
La^{140}	33.0	1.79	18.5
Pr^{143}	30.5	1.53	20
Te^{129}	25.0	0.67	38
Sr^{90}-Y^{90}	15.0	0.19	80
Ce^{141}	13.4	0.35	39
Mo^{99}	10.3	2.2	4.7
	1,070.0	57.0	18.8

5.2.1 Internal Exposure Problem

For the case of a homogeneous reactor in which the fuel in solution is circulated under very high pressure, there is the possibility of a small leak or rupture that would spray radioactive fission products throughout the atmosphere of the working area. The magnitude of such a hazard may be estimated in the following case, in which I^{131} is used as an example.

The possible I^{131} concentration from a small leak is given by:

Equilibrium curies of I^{131}

$$= \frac{4.82 \times 10^{14}}{235} \times \frac{0.602 \times 10^{24}}{3.7 \times 10^{10}} \times 0.03 \times 392^{*} \times 10^{-24}$$

$$= 392 \text{ curies/g of } U^{235}.$$

Assume that 100 liters of solution with its I^{131} content leaked out of the system and was sprayed uniformly throughout a building 60 by 50 by 33.3 meters (1×10^{5} m^3); then

I^{131} leaving = $392 \times 100 \times 1.17 = 4.58 \times 10^{4}$ curies

(% of total core I^{131} leaking out = $\frac{100 \times 100}{19{,}200} = 0.52\%$)

The concentration of I^{131} in the building is given by

$$C = \frac{\text{activity (curies)}}{\text{vol. } (m^3)} = \frac{\text{activity } (\mu c)}{\text{vol. (cc)}} = \frac{4.58 \times 10^{4}}{1 \times 10^{5}} = 0.458 \ \mu c/cc$$

The breathing rate for a person under the strain of excitement following any accident or warning may be assumed to be 500 cc/sec, which is approximately twice the average over a 24-hr period.

Maximum amount of activity as I^{131} allowed to enter respiratory system

$$= 8 \times 10^{-7} \times 2 \times 10^{7} = 16 \ \mu c$$

Maximum amount of air that can be breathed = 16/0.458 = 35 cc

Time for individual to breath enough I^{131} for a 15.7-rem dose quantity to the thyroid = 35 cc/500 = 0.07 sec

In order to indicate the danger of a radioactive leak, it will be assumed that a person will be in the vicinity of an accident for a period of 10 sec and breathing air with the above I^{131} concentration of 0.458 $\mu c/cc$ for this period.

Quantity of I^{131} breathed in 10 sec = $10 \times 500 \times 0.458 = 2290 \ \mu c$

* σ_f of U^{235} corrected for temperature.

The total dose delivered to the thyroid during the year following this exposure would be 15.7 x 2290/16 = 2340 rem. The dose delivered in 8 days after exposure would be approximately 1200 rem. Although this dose is large it cannot be considered lethal since very large doses of I^{131} are given in therapeutic treatment for thyroid disorders. However, a dose of similar magnitude from other radioisotopes, especially bone-seeking isotopes, which may also be involved in a leak would be considered dangerous.

5.2.2 External Exposure Problem

To calculate the total body irradiation from the atmosphere containing fission product activity, assume a spherical volume containing a uniform concentration of activity, s, in d/sec/cc. The intensity of irradiation, I, in photons/cm^2/sec at the center of this sphere resulting from a single source at a distance ρ, assuming no wall scattering, is given by

$$I(\rho) = \frac{S}{4\pi\rho^2}$$

where S = source strength, d/sec. Then

$$dI(\rho) = \frac{dS}{4\pi\rho^2}$$

$$dS = s\ dv$$

where v = volume of the sphere, cc, and

$$dI(\rho) = \frac{s\ dv}{4\pi\rho^2}$$

In spherical coordinates, this becomes

$$dv = \rho^2 d\rho \sin\theta\ d\phi\ d\theta$$

$$I = \int dI(\rho) = \int \frac{s\rho^2\ d\rho\ d\phi \sin\theta\ d\theta}{4\pi\rho^2}$$

$$I = \frac{s}{4\pi}\int_0^R d\rho \int_0^{2\pi} d\phi \int_0^{2\pi} \sin\theta\ d\theta = Rs$$

The gamma flux and dose rate at the center of a building equivalent to a sphere of 1×10^5 m^3 volume containing 0.46 μc of I^{131} per cubic centimeter would be calculated as follows:

$$\text{Equivalent radius} = \sqrt[3]{\frac{1 \times 10^5}{\frac{4}{3} \times \pi}} = 28.8 \text{ meters}$$

$$I = 28.8 \times 100 \times 0.46 \times 10^{-6} \times 3.7 \times 10^{10} = 4.9 \times 10^7 \text{ photons/cm}^2\text{/sec}$$

The I^{131} gamma energies are 0.64 Mev (15%), 0.36 Mev (79%), and 0.28 Mev (6%), with an average of 0.397 Mev. From Fig. 5-3,[5] 1 rem/hr at 0.397 Mev = 1.17×10^6 photons/cm^2/sec gamma flux and dose rate = $4.90 \times 10^7 / 1.17 \times 10^6$ = 42 rem/hr.

6.0 REFERENCES

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(7) H. Lisco, "The Standard Man," in Quarterly Report of Biological and Medical Division, November 1948 - February 1949, ANL-4253, pp. 96-101.

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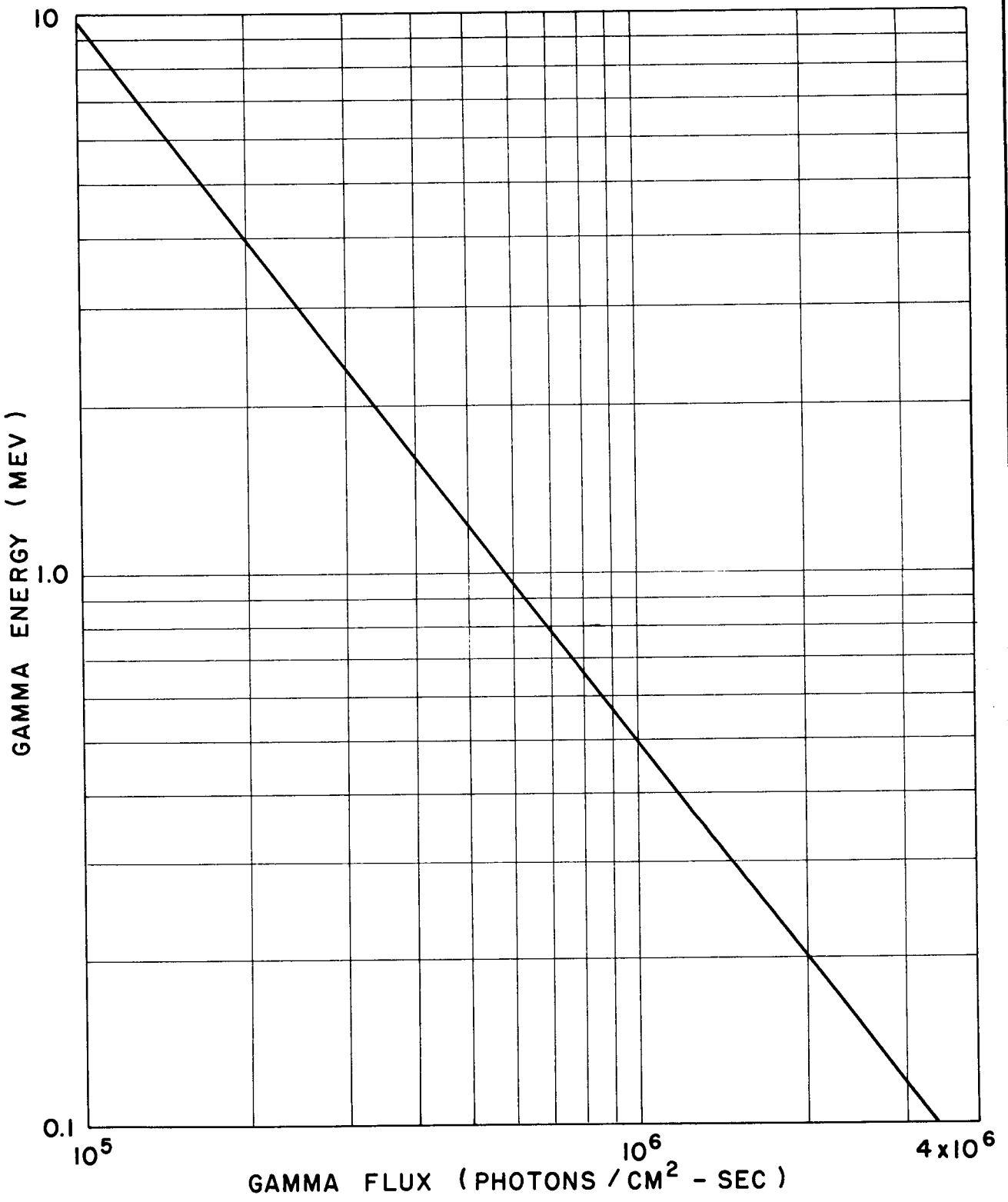

FIGURE 5-3

PLOT OF GAMMA FLUX AS A FUNCTION OF ENERGY FOR ONE ROENTGEN / HOUR RADIATION LEVEL

Appendix

7.0 INFORMATION AND DEFINITIONS PERTAINING TO RADIOLOGICAL PROTECTION

7.1 The Critical Body Organ[2]

In choosing the maximum permissible body burden of a radioisotope the first step is to choose the critical body organ, which is defined as that organ of the body receiving the radioisotope that results in the greatest damage to the body. In most cases it is that organ of the body that accumulates the greatest concentration of the radioactive material and receives the greatest damage. However, this does not necessarily follow since there is great variation in the radiosensitivity of the organs, and some organs are less essential than others to the well-being of the entire body. Which organ is the critical one depends on the method of body intake—ingestion, inhalation, injection, etc.—and may change with time following the intake of the radioactive material. For example, the respiratory tract or the gastrointestinal tract is usually the critical organ if an insoluble compound of a radioactive material is inhaled, but, if it enters the body by way of a contaminated wound, the wound site is usually the critical tissue. If soluble compounds of this same radioactive material are inhaled, the upper respiratory or gastrointestinal tract may be initially the critical organ. In the case of ingestion the gastrointestinal tract is usually the critical organ during the first day following the intake. In the intermediate period the critical organ may be the kidney or liver, and frequently the skeleton is the critical organ for chronic exposure. Usually, but not always, the critical organ for chronic exposure is the organ having the greatest concentration, and frequently it is the organ having the longest biological half-life for the element. The total body becomes the critical organ when the radioelement is rather evenly distributed throughout the body.

7.2 Distribution Fractions and Related Constants[2]

Before beginning a calculation of the body burden and the maximum permissible concentration values the following data must be obtained:

1. Average chemical composition of the body. Values are given in Table 7-1.
2. Mass and effective radius of organs of the body. Values are given in Table 7-2.
3. Characteristics of a "standard man." Values are given in Table 7-3.
4. Average daily ingestion of an element. Values (I) are given in Table 7-4.
5. Fraction of an element passing from the gastrointestinal tract to the blood. Values (f_1) are given in Table 7-4.
6. Fraction passing from blood to critical body organ. Values (f'_2) are given in Table 7-4.
7. Fraction in critical organ of that in the total body. Values (f_2) are given in Table 7-4.
8. Fraction of that taken into the body which is retained in the critical organ. Values for this (designated by f_a in the case of inhalation and by f_w in the case of ingestion) are given in Table 7-4.

For cases of inhalation of soluble material, $f_a = (0.25 + 0.5f_1)f'_2$. When the value of f'_2 is unknown, it is replaced by f_2, as a rough approximation. When the lung is taken as the critical organ, f_a is taken as the approximation $1 - f_1$. In all cases considered, the estimated dose to the lungs from inhalation of soluble compounds was less than the dose to the gastrointestinal tract. Therefore these values based on the lungs as the critical organ were omitted from Table 7-4.

For cases of inhalation of insoluble and slightly soluble material, a portion of the gastrointestinal tract or the lung is usually the critical organ. Unless data are available for the specific radioactive dust particles, it is assumed in the case of the lungs that $f_a = 0.12$. In the case in which some of the radioactive material is swallowed, so that it irradiates a portion of the gastrointestinal tract as the critical tissue, the value of f_a is given by the expression $0.625\ (1 - f_1)$.

For cases of ingestion of soluble compounds, $f_w = f_1 f_2'$ and f_2 is sometimes used in place of f_2' if no better information is available.

For cases of ingestion of insoluble compounds, a portion of the gastrointestinal tract is the critical tissue and $f_w = 1 - f_1$.

9. Average concentration of the element in the critical organ. Values are given in Table 7-4.

10. Factors of nonuniform distribution in the critical organ. This factor, N, is taken as 5 relative to radium for all alpha-emitting radioisotopes that are bone-seeking elements. It is also taken as 5 relative to light-particle-emitting radioisotopes uniformly distributed in the bone in such a manner as to deliver a dose rate of 0.3 rem/week for the light-particle energy components of nuclear disintegration—beta particles, positrons, and internally converted electrons—of all bone-seeking radioisotopes except P^{32}. This factor is assumed to be 1 for X and gamma radiation regardless of the organ that receives the radiation, and is also assumed to be 1 for all organs except bone regardless of the type of radiation.

7.3 Effective Half-life[2]

In cases of continuous exposure, the effective half-life determines when equilibrium is reached in a body organ and the concentration of the radioisotope in air or water determines the dose rate to the critical body organ when equilibrium is reached. The effective half-life, T, is determined by the sum of the rates of radioactive decay and biological elimination and is given by the equation

$$T = \frac{T_b T_{1/2}}{T_b + T_{1/2}}$$

where T = effective half-life;

$T_{1/2}$ = radioactive half-life;

T_b = biological half-life.

Table 7-1

Average Chemical Composition of the Adult Human Body

Element	Percentage by Weight in Body	Approximate Amount in a 70-kg Man (g)
Oxygen	65.0	45,500
Carbon	18.0	12,600
Hydrogen	10.0	7,000
Nitrogen	3.0	2,100
Calcium	1.5	1,050
Phosphorus	1.0	700
Sulfur	0.25	175
Potassium	0.2	140
Sodium	0.15	105
Chlorine	0.15	105
Magnesium	0.05	35
Iron	0.004	3
Manganese	0.0003	0.2
Copper	0.0002	0.1
Iodine	0.00004	0.03

Table 7-2

Mass and Effective Radius of Organs of the Adult Human Body [a]

	Mass, m (g)	Percentage of Total Body [b] Weight	Effective Radius, x (cm)
Total body [b]	70,000	100	30
Muscle	30,000	43	30
Skin and subcutaneous tissue [c]	6,100	8.7	0.1
Fat	10,000	14	20
Skeleton without bone marrow	7,000	10	5
Red marrow	1,500	2.1	
Yellow marrow	1,500	2.1	
Blood	5,400	7.7	
Gastrointestinal tract [b]	2,000	2.9	30
Contents of gastrointestinal tract			
Stomach	250		
Small intestine	1,100		
Upper large intestine	135		
Lower large intestine	150		5
Liver	1,700	2.4	10
Brain	1,500	2.1	
Lungs(2)	1,000	1.4	30
Lymphoid tissue	700	1.0	
Kidneys(2)	300	0.43	7
Heart	300	0.43	
Spleen	150	0.21	7
Urinary bladder	150	0.21	
Pancreas	70	0.10	
Salivary glands(6)	50	0.071	
Testes(2)	40	0.057	
Spinal cord	30	0.043	
Eyes(2)	30	0.043	
Thyroid gland	20	0.029	3
Teeth	20	0.029	
Prostate gland	20	0.029	
Adrenal glands(2)	20	0.029	
Thymus	10	0.014	
Miscellaneous (blood vessels, cartilage, nerves, etc.)	390	0.56	

[a] Reference 7.

[b] Does not include contents of gastrointestinal tract.

[c] The mass of the skin alone is taken as 2000 g.

Table 7-3

Characteristics of a "Standard Man"

Water intake in food	700 cc/day
Water intake as fluids	1500
	2200 cc/day
Water of oxidation	300
Total water consumption	2500 cc/day
Water excretion as sweat	500 cc/day
Water excretion from lungs	400
Water excretion by feces	100
Water excretion by urine	1500
Total water excretion	2500 cc/day
Air inhaled during 8-hr work day	10^7 cc/day
Air inhaled during 16-hr not at work	10^7
Total air inhaled	2×10^7 cc/day
CO_2 in alveolar air	5.5%
Interchange area of lungs	50 m^2
Area of upper respiratory tract, trachea, bronchials	20
Total surface area of respiratory tract	70 m^2
Total water in body	50 kg
Average life span of man	70 years
Occupational exposure of man	8 hr/day, 40 hr/week, 50 weeks/year
Depth of blood-forming organs	5 cm
Minimum thickness of epidermis	0.07 mm

Particulates in Respiratory Tract. Retention of particulate matter in the lungs depends on many factors, such as size, shape, and density of the particles, the chemical form, and whether or not the person is a mouth breather; however, when specific data are lacking the distribution is assumed to be:

	% of Readily Soluble Compounds	% of Other Compounds
Exhaled	25	25
Deposited in upper respiratory passages and later swallowed	50	50
Deposited in lower respiratory passages	25 (taken up in body)	25[a]

[a] Half of this is eliminated from the lungs and swallowed in the first 24 hr, making a total of 62.5% swallowed. The other 12.5% is retained in the lungs with a half-life of 120 days, assuming that this is taken up into body fluids.

Table 7-4

Normal Behavior of Elements in the Human Body[a]

Element	I (g/d)	Total Body				Critical Organ — 1st Choice							Critical Organ — 2nd Choice					
		f_1	f_a	T_b	C	Name	f_2	f_w	f_a	T_b	C	f_2'	Name	f_2	f_w	f_a		C
Mn	4×10^{-3}	0.1	0.3	2.6	3×10^{-6}	Kidneys	0.09	0.004	2×10^{-21}	2.5	6×10^{-7}	0.08	Liver	0.16	0.01	0.09	5	2×10^{-6}
Fe	0.012	0.8	0.65		4×10^{-5}	Blood	0.64	0.8	0.65	65	5×10^{-4}	1.0						
Ni	Trace	0.2	0.35			Liver	0.68	0.004	0.007	8	Trace	0.02						
Cu	0.002	0.28	0.39		2×10^{-6}	Liver	0.08	0.09	0.13	39	6×10^{-6}	0.33	Eyes	5×10^{-4}	1×10^{-3}	0.002	21	3×10^{-6}
Zn	0.017	0.1	0.35			Bone	0.15	2×10^{-2}	5×10^{-2}	23	1×10^{-4}	0.15						
Ga		0.001	0.25	5		Bone	0.82	4×10^{-4}	0.1	3×10^{3}	$<1\times10^{-6}$	0.4						
Ge		0.01	0.25	2		Kidneys	0.35	2×10^{-4}	5×10^{-3}	6		0.02						
As		0.03	0.26	280		Kidneys	0.02	3×10^{-4}	3×10^{-3}	37		0.01	Bone	0.04	9×10^{-4}		120	
Rb		1.00	0.75	13		Muscle	0.54	0.42	0.33	13		0.44						
Sr	3×10^{-4}	0.6	0.55	190		Bone	0.7	0.25	0.22	4×10^{3}	6×10^{-5}	0.4						
Y		0.0005	0.25	550		Bone	0.65	3×10^{-4}	0.14	>500		0.55	Lungs	0.004	2×10^{-6}		34	
Zr		0.0005		5000		Bone	0.62	10^{-4}	0.058	180		0.23						
Nb		0.45	0.47	73		Bone	0.4	0.13	0.12	50		0.25						
Mo	Trace	0.7	0.6			Bone	0.5	2×10^{-4}	2×10^{-4}	150	Trace	3×10^{-4}						
Ru		<0.0005	0.25	86		Kidneys	0.04	2×10^{-5}	0.01	20		0.04						
Rh		0.2	0.35	18		Kidneys	0.08	0.01	2×10^{-2}	28		0.05						
Ag		0.02	0.26	2		Liver	0.1	1×10^{-4}	2×10^{-3}	3		0.006						
Sn		0.0087	0.25	67		Bone	0.8	0.0026	0.076	72		0.3	Lungs	0.007	3×10^{-5}		150	
Te		0.25	0.37	1700		Kidneys	0.2	7×10^{-4}	0.02	15		0.006						
I	2×10^{-4}	1.00	0.75	130	4×10^{-7}	Thyroid	0.2	0.2	0.15	180		0.2						
Xe						T.Body												
Cs		1.00	0.75	25		Muscle	0.45	0.48	0.36	17		0.48						
Ba		0.1	0.35	120		Bone	0.96	0.07	0.2	~200		0.7						
La		0.003	0.25	23		Bone	0.3	1×10^{-3}	0.1	35		0.4						
Ce	Trace	0.0005	0.25	330		Bone	0.8	2×10^{-4}	0.1	500	Trace	0.4						
Pr		0.005	0.25	420		Bone	0.6	1×10^{-3}	0.063	50		0.25						
Pm		0.0005	0.25	48		Bone	0.7	2×10^{-4}	0.09	100		0.35						
Sm		0.0001	0.25	5		Bone	0.65	3×10^{-5}	0.05	4×10^{4}		0.2	Spleen	0.006	4×10^{-7}		5	
Eu		0.0005	0.25	360		Bone	0.7	2×10^{-4}	0.09	1400		0.35	Spleen	0.004	2×10^{-6}		850	
Th		0.0005	0.25	180		Bone	0.82	4×10^{-4}	0.2	4×10^{4}		0.78						
Pa		0.0005		270		Bone	0.65	2×10^{-4}	~0.12	400		0.45						
U	2x10-6	0.0005	0.25			Kidneys	0.065	2×10^{-4}	0.08	30	2×10^{-8}	0.33	Bone	0.05	10^{-4}	0.05	300	10^{-9}
Np		0.0005		42		Bone	0.93	5×10^{-4}		100		0.65						
Pu		0.0001	0.25			Bone	0.75	1×10^{-4}	0.18	4.3×10^{4}		0.7	Lungs	(1.0)		(0.12)	(360)	
Am		0.0005	0.25	1100		Bone	0.9	1×10^{-4}	0.063	890		0.25						
Cm		0.0005	0.25	440		Bone	0.9	1×10^{-4}	0.063	600		0.25						

[a]The values given for f_1, f_2', f_w, f_a, and T_b are for soluble compounds except in cases where the lungs are given as the critical organs.

I = Normal daily intake of element in grams.
f_1 = Fraction going from the gastrointestinal tract to the blood.
f_2 = Fraction in critical organ of that in total body.
f_2' = Fraction going from blood to critical organ.
f_w = Fraction ingested that is retained in critical organ.
f_a = Fraction inhaled that is retained in critical organ.
T_b = Biological half-life or time required for removal of half of the element from the organ by biological processes (days).
C = Concentration in organ, g of element/g of tissue.

Actually, the biological elimination from the body does not follow a simple exponential decay but a more complex pattern. However, in most cases, after the initial distribution and readjustment of the radioisotope from one body organ to other, the decay curve is usually close to a simple exponential, as indicated by the portion of the curve from b to c in Fig. 7-1.

7.4 Product of Effective Energy, Relative Biological Effectiveness, and Nonuniform Distribution Factor (2)

This term, E(RBE)N, is the product of (1) the effective energy, E, in mega electron volts, delivered to the critical organ per disintegration of the radioisotope, (2) the relative biological effectiveness, RBE, of the radiation relative to 200-kv X radiation, and (3) a nonuniform distribution factor, N, which is assumed to be 1 for X and γ radiation, for deposition in any organ and 5 for the alpha particle, beta particle, positron and internally converted electron, and atomic recoil components of energy from radioisotopes deposited in the bone (except Ra^{226} and P^{32}) and is taken as 1 for all body organs except bone for these radiation particles.

7.5 Units of Dose of Ionizing Radiation (2)

1 esu per cubic centimeter of air = 83.9 ergs per gram of air per roentgen;
1 roentgen = 93 ergs per gram of tissue.

The unit of ionizing radiation used in this reference is called the "rad," which is defined as the amount of ionizing radiation that gives 100 ergs per gram of human tissue at the point in question; a unit used in this study as well as the reference is the "rem," which is defined by the relation

$$1 \text{ rem} = \frac{1 \text{ rad}}{\text{RBE}} = \frac{100 \text{ ergs per gram of tissue}}{\text{RBE}}.$$

7.6 Maximum Permissible Body Burden

In the case of alpha-emitting radioisotopes that localize in the bone, the maximum permissible body burden, q, is determined by a direct comparison of the radioactive material with radium. There has been a long-established value of 0.1 μc as the maximum permissible body burden for radium, and it is known

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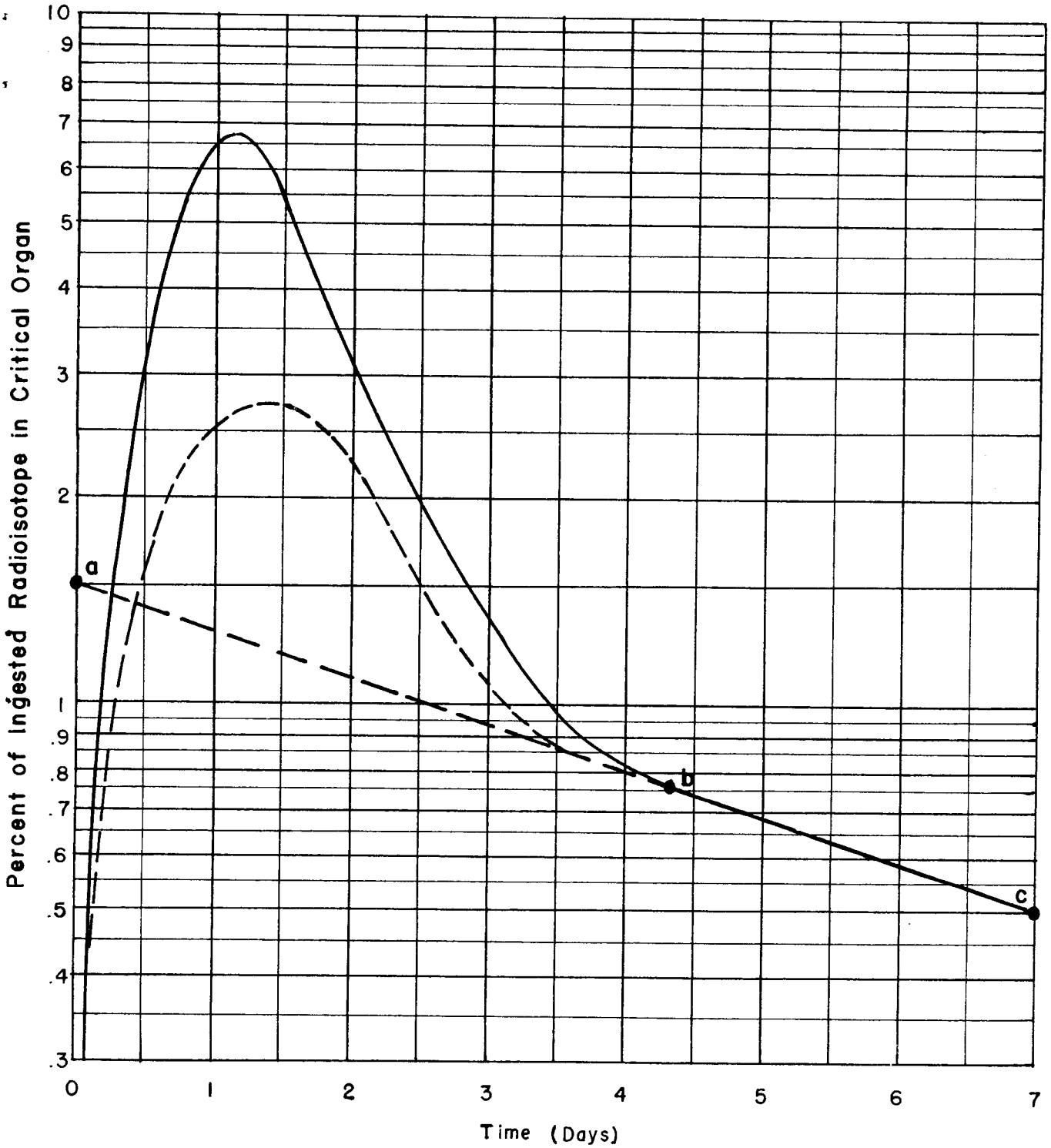

Figure 7-1

Deposition and Elimination of a Radioisotope in a Critical Body Organ Following a Single Ingestion

that 99% of all radium distributes itself uniformly throughout the skeleton. The product of effective energy, relative biological effectiveness, and the nonuniform distribution factor for radium has been established as 162.[1,2] The maximum permissible body burden of all alpha emitters is therefore given in microcuries by the equation

$$q = \frac{0.1(0.99)}{f_2} \times \frac{162}{\Sigma E(RBE)N} = \frac{16}{f_2 \Sigma E(RBE)N}.$$

The values of maximum permissible body burden for beta and gamma emitting radioisotopes and the maximum permissible concentrations in air and water for all radioisotopes are developed on the premise that the maximum permissible concentration in air or water is that which will permit the accumulation of a burden of the radioisotope in the critical body organ so that it will receive an average dose rate of 0.3 rem/week after the contaminated air or water has been used exclusively for a time that is much larger than the effective half-life but not greater than 70 years in any case. The value of maximum permissible body burden for these radioisotopes is given in microcuries by the equation

$$q = \frac{100\ mW}{3.7 \times 10^4 \times 1.6 \times 10^{-6} \times 6.05 \times 10^5 f_2 \Sigma E(RBE)N}$$

$$= \frac{2.8 \times 10^{-3}\ mW}{f_2 \Sigma E(RBE)N} = \frac{8.4 \times 10^{-4}\ m}{f_2 \Sigma E(RBE)N}$$

where

3.7×10^4 = factor for converting disintegrations per second to microcuries;

1.6×10^{-6} = factor for converting ergs to million electron volts;

6.05×10^5 = factor for converting seconds to weeks;

100 = factor for converting ergs per gram to rads;

W = maximum permissible weekly dose = 0.3 rem;

m = mass of critical organ, grams.

7.7 Maximum Permissible Concentration (MPC) in Air and Water

The maximum permissible concentration of a radioisotope is found by integrating from time 0 to time t the equation

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

where qf_2 = burden of radioisotopes in critical organ, μc;

λ = effective decay constant, $0.693/T$;

P = rate of uptake by the critical organ, μc/day which is equal to $(MPC)r$, where r is $2200f_w$ for water and $2 \times 10^7 f_a$ for air;

t = period of exposure, days;

$$(MPC)_a = \frac{3.5 \times 10^{-8} qf_2}{Tf_a(1-e^{-0.693t/T})} ;$$

$$(MPC)_w = \frac{3.1 \times 10^{-4} qf_2}{Tf_w(1-e^{-0.693t/T})} .$$

Values of $(MPC)_a$ and $(MPC)_w$ are given in Table 7-5.

7.8 Dose and Air or Water Concentration for a Single Exposure[3]

The total integrated dose delivered to a critical organ in t days following a single exposure is given by the equation

$$D = \frac{73.9f_a \text{ (or } f_w) \; I_o T \Sigma E(RBE)N \; (1-e^{-0.693t/T})}{m}$$

where I_o = amount (μc) of radioisotope taken into body, and is equal to $2200\ (MPSEV)_w$ or $2 \times 10^7 (MPSEV)_a$ for the maximum single exposure cases;

volume of water taken into body per day = 2200 cc;
volume of air taken into body per day = 2×10^7 cc;

$(MPSEV)_{w \text{ or } a}$ = maximum permissible concentration(μc/cc) of radioisotope in water for a single exposure, which is based on 1 days' intake time.

Table 7-5

Reactor Irradiation Product Data, Maximum Permissible Body Burden, and Maximum Concentration in Air and Water for Continuous Exposure[1,2]

Isotope	Radioactive Half-life, $T_{1/2}$ (days)	Critical Organ	$\Sigma E(RBE)N$	Effective Half-life, T (days)	Maximum Permissible Total Body Burden, q (μc)	Maximum Permissible Concentration (μc/cc)	
						In Water	In Air
Mn^{56}	0.108	Kidneys	1.1	0.104	2	0.15	3×10^{-6}
Fe^{55}	1060	Blood	0.006	61	1000	0.005	7×10^{-7}
Fe^{59}	46.3	Blood	0.54	27	13	0.0001	2×10^{-8}
Ni^{59}	9.1×10^{7}	Liver	0.05	8	42	0.3	2×10^{-5}
Cu^{64}	0.54	Liver	0.15	0.53	120	0.06	5×10^{-6}
Zn^{65}	250	Bone	0.097	21	400	0.06	2×10^{-6}
Ga^{72}	0.59	Bone	2.6	0.59	3	3	1×10^{-6}
Ge^{71}	11.4	Kidneys	0.01	3.9	72	10	4×10^{-5}
As^{76}	1.12	Kidneys	1.1	1.08	11	0.2	2×10^{-6}
Sr^{89}	53	Bone	2.8	52	2	7×10^{-5}	2×10^{-8}
Sr^{90} - Y^{90}	9100	Bone	5.1	2700	1	8×10^{-7}	2×10^{-10}
Y^{91}	57	Bone	2.8	51	3	0.01	9×10^{-9}
Nb^{95}	35	Bone	0.33	21	44	0.002	2×10^{-7}
Zr^{95} - Nb^{95}	65 + 35	Bone	0.77 + 0.33	48 + 21	10	0.3	8×10^{-8}
Mo^{99}	285	Bone	0.69	2.8	17	5	6×10^{-4}
Ru^{106} + Rh^{106}	365	Kidneys	1.4	19	4	0.1	3×10^{-8}
Rh^{105}	1.52	Kidneys	0.33	1.5	9	0.4	2×10^{-6}
Ag^{111}	7.5	Liver	0.37	2.1	39	5	3×10^{-5}
Sm^{113}	112	Bone	0.087	44	84	0.2	6×10^{-7}
Te^{127}	90.4	Kidneys	0.28	13	4	0.03	1×10^{-7}
Te^{129}	32	Kidneys	0.89	10	1.4	0.01	4×10^{-8}

Table 7-5, Continued

Isotope	Radioactive Half-life, $T_{1/2}$ (days)	Critical Organ	$\Sigma E(R\Phi)N$	Effective Half-life, T (days)	Maximum Permissible Total Body Burden, q (μc)	Maximum Permissible Concentration (μc/cc)	
						In Water	In Air
I^{131}	8	Thyroid	0.22	7.7	0.6	6×10^{-5}	6×10^{-9}
Xe^{133}	5.27	Total body	0.18		320	4×10^{-3}	4×10^{-6}
Xe^{135}	0.38	Total body	0.56		100	0.001	2×10^{-6}
$Cs^{137} + Ba^{137m}$	1.2×10^{4}	Muscle	0.57	17	98	2×10^{-3}	2×10^{-7}
$Ba^{140} + La^{140}$	12.8	Bone	4.3	12	1	5×10^{-4}	2×10^{-8}
La^{140}	1.67	Bone	2.9	1.6	7	0.3	4×10^{-7}
$Ce^{144} + Pr^{144}$	275	Bone	6.3	180	1	8×10^{-3}	2×10^{-9}
Pr^{143}	13.8	Bone	1.6	11	6	0.08	2×10^{-7}
Pm^{147}	1460	Bone	0.34	140	25	0.2	4×10^{-8}
Sm^{151}	3.6×10^{5}	Bone	0.10	3.9×10^{4}	90	0.05	3×10^{-9}
Eu^{154}	1970	Bone	1.2	820	7	0.01	2×10^{-9}
Th-Nat.	5×10^{12}	Bone	1866	4.3×10^{4}	0.01	5×10^{-7}	3×10^{-11}
$Th^{234} + Pa^{234}$	24.1	Bone	4.3	24.1	2	5×10^{-2}	10^{-8}
Pa^{233}	27.4	Bone	0.34	25.6	27	1	2×10^{-7}
U-Nat. (s)	1.64×10^{12}	Kidneys	94	30	0.04	10^{-4}	3×10^{-11}
U-Nat. (i)	1.64×10^{12}	Lungs	94	120	0.01		3×10^{-11}
U^{233} (s)	5.9×10^{7}	Bone	250	300	0.04	1.5×10^{-4}	3×10^{-11}
U^{233} (i)	5.9×10^{7}	Lungs	50	120	0.016		3×10^{-11}
Pu^{239} (s)	8.8×10^{6}	Bone	267	4.3×10^{4}	0.04	6×10^{-6}	2×10^{-12}
Pu^{239} (i)	8.8×10^{6}	Lungs	54	360	0.02		2×10^{-12}
Am^{241}	1.79×10^{5}	Bone	282	890	0.06	2×10^{-4}	4×10^{-11}
Cm^{242}	150	Bone	314	120	0.06	10^{-3}	2×10^{-10}