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ABSTRACT

Radiation protection regulations in the United States have evolved from the recommendations of the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP). In 1959, the ICRP issued Publication 2 which contained specific recommendations on dose rate limits, permissible body burdens, metabolic data for radionuclides, and maximum permissible concentrations (MPC) in air or water. Over the next 20 years, new information became available concerning the effects of radiation, the uptake and retention of radionuclides, and the radioactive decay schemes of parent radionuclides. To include this newer information, the ICRP issued Publication 30 in 1978 to supersede Publication 2. One of the secondary limits defined in Publication 30 is the annual limit of intake (ALI). Radionuclide specific ALI values are intended to replace MPC values in determining whether or not ambient air and water concentrations are sufficiently low to maintain the dose to workers within accepted dose rate limits. In this paper, we discuss the derivation of MPC and ALI values, compare inhalation committed dose equivalent factors derived from ICRP Publications 2 and 30, and discuss the practical implications of using either MPC or ALI in determining compliance with occupational exposure limits. For most radionuclides, ICRP Publication 30 inhalation committed dose equivalent factors are within a factor of 5 of inhalation committed dose equivalent factors based on ICRP Publication 2. A notable exception occurs for the isotopes of uranium, where the Publication 30 committed dose equivalent factors are about 20 times higher than the Publication 2 committed dose equivalent factors. This increase is due in part to the application of the task group lung model, and in part to the use of updated metabolic data.

INTRODUCTION

Over the years, the ICRP has defined primary and secondary limits on radiation exposure and radionuclide intake in an attempt to prevent or minimize somatic and genetic injuries caused by radiation. In 1959, the ICRP issued Publication 2 with specific recommendations in the form of dose rate limits, maximum permissible body burdens, metabolic data for radionuclides, and maximum permissible concentrations (MPC) of specific radionuclides in air or water. These MPC values are further recommended to serve as a guide to indicate if occupational procedures are adequate to maintain the dose to workers from internally deposited radionuclides within the dose rate limits recommended by the ICRP. Occupational MPC values are based on the recommendation that the internal dose rate after 50 years of occupational exposure (i.e., 40 hours per week, 50 weeks per year, for 50 years) does not exceed the defined dose rate limit for critical organs. Over the next 20 years, new information became available concerning the effects of radiation, the uptake and retention of radionuclides in the body, and the decay schemes of various radionuclides. Also, the concept of MPC had been misused to imply a concentration in air or water that could never be exceeded under any conditions. Thus, the ICRP felt the need to update its recommendations by issuing new reports.

ICRP Publication 30 was issued in 1978 to supersede ICRP Publication 2. It concerns new primary and secondary standards designed to limit the intake of radionuclides. One of the secondary limits defined is the annual limit of intake (ALI) for selected radionuclides. These ALI values are intended to replace MPC values in practice, stressing the importance of assessing body intakes versus assessing average air or water concentrations. The purpose of this paper is to further discuss the derivation of MPC and ALI values, to compare the committed dose equivalent factors used in their calculation, and to discuss the practical implications of using either MPC or ALI in determining compliance with occupational exposure limits.

ICRP PUBLICATION 2 - $(MPC)_a$

In ICRP Publication 2, calculated $(MPC)_a$ values are provided for the more important radionuclides, and they are applicable primarily to

occupational exposure. For organs other than the gastrointestinal (GI) tract, the $(MPC)_a$ values are calculated by first relating the rate that material is transferred into an organ (P μCi/day) to the rate material leaves an organ, shown in Equation 1.

$$P = \frac{d(qf_2)}{dt} + \lambda(qf_2) \qquad (1)$$

where:

- P • the uptake of a radionuclide by a critical body organ (μCi/day)
- q • the body burden of the radionuclide (μCi)
- f_2 • the fraction of the body burden of a radionuclide in the critical organ of the body (dimensionless)
- λ • the effective decay constant, (0.693/T); where T = $(T_r\ T_b)/T_r + T_b)$, (days); and where T_r is the radioactive half-life (days) and T_b is the biological half-life (days) and
- t • the period of exposure; for occupational exposure assumed to be 50 years.

The burden in the critical organ is the product qf_2, and when qf_2 and t equal zero, the solution to Equation 1 is shown in Equation 2.

$$P = \frac{qf_2\lambda}{(1-e^{-\lambda t})} \qquad (2)$$

The uptake of a radionuclide by the critical organ, P, also equals the product of M, the concentration of a radionuclide in air taken into the body, and S, the average rate of intake of air (cm^3/day) times f_a, the fraction of the radionuclide intake arriving in the critical body organ. For the average occupational exposure calculation, the standard man is assumed to work 8 hours per day, 5 days per week, 50 weeks per year. In a 24-hour day, the standard man is assumed to inhale 2×10^7 cm^3 of air, half of which is inhaled during the working day. Thus, for average occupational

exposure $S = 10^7 \cdot (5/7) \cdot (50/52) f_a$. Substituting for P and λ in Equation 2, $(MPC)_a$ values are calculated using Equation 3.

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

Thus, $(MPC)_a$ is a function of T, f_a, and f_2 which are defined from metabolic data listed for each radionuclide.

ICRP PUBLICATION 30 - ALI

In ICRP Publication 30, the ICRP revised its recommendations to include the changes outlined in ICRP Publication 26. Using current information on the risk of radiation-induced fatal cancer or serious genetic defects, the recommendations in ICRP 26 are based on the assumption that these effects are linearly related to dose equivalent without threshold. Thus, the risk of fatal cancer or hereditary disease is determined by the total dose equivalent received by the exposed individuals or by the collective dose equivalent within the group or population exposed, independent of the dose-equivalent rate or any fractionation. Based on this theory, the main principals of the new dose limitation system are:

1) all practices adopted shall produce a positive net benefit;

2) all exposures shall be kept as low as reasonably achievable (taking economic and social factors into account as well); and

3) the dose equivalent to individuals shall not exceed the limits recommended by the ICRP.

ICRP Publication 30 was issued to explain the derivation of secondary standards that limit the intake of radionuclides by workers in compliance with principal 3.

In ICRP Publication 26, dose limits are defined for stochastic and non-stochastic effects. The dose limit defined for stochastic effects, or those malignant and hereditary diseases for which the probability of occurrence is regarded as a function of dose without threshold, is 5 rem (or 50 mSv)

in any year. The dose limit for non-stochastic effects, or those effects for which a threshold or pseudo-threshold of dose must be exceeded before an effect is induced, is 50 rem (or 0.5 Sv) to any tissue except the lens of the eye where a limit of 30 rem (or 0.3 Sv) applies. Thus, the basic conditions for limiting the exposure of workers are:

$$\sum_T w_T H_{50,T} \leq 5 \text{ rem } (0.05 \text{ Sv}) \tag{4}$$

and

$$H_{50,T} \leq 50 \text{ rem } (0.5 \text{ Sv}) \tag{5}$$

for stochastic and non-stochastic effects respectively, and where:

- $H_{50,T}$ • the Committed Dose Equivalent received by tissue T, (rem or Sv)
- w_T • a weighting factor representing the ratio of the stochastic risk resulting from tissue T to the total risk when the whole body is irradiated uniformly.

With these stochastic and non-stochastic dose limits, the annual limits of intake (ALI) for various radionuclides are derived as secondary limits. The ALI is defined to be the greatest value of the annual intake I, which satisfies both of the following inequalities:

$$I \sum_T w_T \, (H_{50,T} \text{ per unit intake}) \leq 5 \text{ rem } (0.05 \text{ Sv}) \tag{6}$$

and

$$I \, (H_{50,T} \text{ per unit intake}) \leq 50 \text{ rem } (0.5 \text{ Sv}) \tag{7}$$

where w_T and $H_{50,T}$ are previously defined and where:

I • the annual intake of the specified radionuclide by ingestion or inhalation.

Calculated values of the ALI for specific radionuclides are listed in ICRP Publication 30 and its supplements.

A comparison of the occupational dose limits defined in ICRP Publications 2 and 26 is given in Table 1. The basic difference in the limits shown is the adoption of the uniform non-stochastic organ limit of 50 rem per year (0.5 Sv per year). The exception is to the lens of the eye where an annual limit of 30 rem per year (0.3 Sv per year) applies.

As an additional secondary limit, the derived air concentration (DAC) is defined. The ICRP notes that the $(MPC)_a$ values defined in ICRP Publication 2 have been misused to infer an overexposure even when they have been exceeded for only a short period of time. It is emphasized that the real limit for inhalation is the ALI, but DAC values are listed for an occupational exposure of one year based on the intake resulting in the ALI for that year. Thus, DAC and $(MPC)_a$ values can not be directly compared because DAC values are calculated based on one year of intake, and $(MPC)_a$ values are based on 50 years of intake. A more fundamental comparison can be made of the committed dose equivalent factors used to derive the limits in ICRP Publications 2 and 30, as described in the next section of this paper.

INHALATION COMMITTED DOSE EQUIVALENT FACTORS

Since the methods used to derive MPC and ALI values are quite different, it is impossible to directly compare their values. However, we can compare the inhalation committed dose equivalent factors calculated by each method. The results of this comparison are shown in Table 2 for 67 radionuclides. Inhalation committed dose equivalent factors (over 50 years) are obtained from NUREG-0172 (1977) for the ICRP Publication 2 method and directly from ICRP Publication 30, Part 1 (1979). The far right-hand column in Table 2 contains the ratio of organ-specific dose rate factors (ICRP Publication 30 divided by ICRP Publication 2). For most radionuclides, the two methods

TABLE 1. Annual Occupational Radiation Dose Limit Comparison

Publication Number	Internal Limits(rem/yr)			External Limits(rem/yr)			Comments
	Bone	Thyroid	Other Organs	Lens of the Eye	Skin	Total Body	
ICRP 2	30	30	15	5	30	5	The dose to gonads or to the total body at age N shall not exceed 5 (N-18).
ICRP 26	50	50	50	30	50	5	A stochastic annual limit for uniform total body exposure of 5 rem/year. For internal organs, a non-stochastic limit of 50 rem per year applies to all organs except the lens of the eye.

TABLE 2. Committed Dose Equivalent Factor Comparison for Inhalation

Radionuclide	Critical Organs	Committed Dose Equivalent Factors ICRP 2 (NUREG-0172) (mrem/pCi)	ICRP 2 (NUREG-0172) (Sv/Bq)	ICRP 30 Critical Organ (Sv/Bq)	ICRP 30 Weighted Total Body (Sv/Bq)	Critical Organ Ratio[a] (ICRP 30 / NUREG-0172)
^{3}H	Body Tissue	1.6-7	4.3-11	1.7-11	1.7-11	.39
^{32}P	Bone	1.6-4	4.3-8	6.0-9	3.6-9	.14
^{54}Mn	Lung	1.8-4	4.9-8	6.7-9	1.7-9	.14
^{56}Mn	GI(LLI)	2.5-6	6.8-10	2.0-10	6.4-11	.29
^{57}Co	Lung	4.6-5	1.2-8	1.7-8	2.0-9	1.4
^{58}Co	Lung	1.2-4	3.2-8	1.6-8	1.9-9	.50
^{60}Co	Lung	7.5-4	2.0-7	3.4-7	4.1-8	1.7
^{89}Sr	Bone	3.8-5	1.0-8	8.4-9	1.0-8	.84
^{90}Sr	Bone	6.3-3	1.7-6	7.3-7	3.4-7	.20
^{91}Sr	GI(LLI)	2.4-5	6.5-9	1.2-9	4.0-10	.18
^{92}Sr	GI(ULI)	5.4-6	1.5-9	6.1-10	2.1-10	.41
^{93}Zr	Lung	2.1-5	5.7-9	8.7-8	1.9-8	15.
^{95}Zr	Lung	2.2-4	5.9-8	4.1-8	4.9-9	.70
^{97}Zr	GI(LLI)	6.5-5	1.8-8	5.1-9	1.1-9	.28
^{93m}Nb	Lung	3.1-5	8.4-9	6.4-8	7.7-9	7.6
^{95}Nb	Lung	6.3-5	1.7-8	8.3-9	1.2-9	.49
^{97}Nb	GI(ULI)	3.0-8	8.1-12	--[b]	1.9-11	--[b]
^{99}Mo	GI(LLI)	3.1-5	8.4-9	5.5-9	9.9-10	.66
^{125m}Te	Lung	3.9-5	1.0-8	1.0-8	1.8-9	1.0
^{127m}Te	Lung	1.2-4	3.2-8	3.3-8	5.2-9	1.0
^{127}Te	GI(LLI)	7.2-6	1.9-9	2.3-10	7.8-11	.12
^{129m}	Lung	1.4-4	3.8-8	4.0-8	5.5-9	1.0
^{129}Te	GI(ULI)	2.0-8	5.4-12	--[b]	1.8-11	--[b]
^{131m}Te	GI(LLI)	7.0-5	1.9-8	2.4-9	1.5-9	.13
^{132}Te	GI(LLI)	6.4-4	1.7-7	--[b]	2.1-9	--[b]
^{129}I	Thyroid	5.5-3	1.5-6	1.6-6	4.7-8	1.1
^{131}I	Thyroid	1.5-3	4.0-7	2.9-7	8.8-9	.72
^{132}I	Thyroid	1.4-5	3.8-9	1.7-9	9.1-11	.45
^{133}I	Thyroid	2.7-4	7.3-8	4.9-8	1.5-9	.67

TABLE 2. (Continued)

Radionuclide	Critical Organs	Committed Dose Equivalent Factors ICRP 2 (NUREG-0172) (mrem/pCi)	ICRP 2 (NUREG-0172) (Sv/Bq)	ICRP 30 Critical Organ (Sv/Bq)	ICRP 30 Weighted Total Body (Sv/Bq)	Critical Organ Ratio[a] (ICRP 30 / NUREG-0172)
^{134}I	Thyroid	3.7-6	1.0-9	2.9-10	3.0-11	.29
^{135}I	Thyroid	5.6-5	1.5-8	8.5-9	3.0-10	.57
^{134m}Cs	GI(ULI)	7.9-9	2.1-12	--[b]	9.7-12	--[b]
^{134}Cs	Lung	1.2-5	3.2-9	1.2-8	1.2-8	3.8
^{135}Cs	Liver	1.3-5	3.5-9	--[b]	1.2-9	--[b]
^{136}Cs	Lung	1.5-6	4.0-10	2.3-9	2.0-9	5.8
^{137}Cs	Lung	9.4-6	2.5-9	8.8-9	8.7-9	3.5
^{141}Ce	Lung	4.5-5	1.2-8	1.7-8	2.2-9	1.4
^{143}Ce	GI(LLI)	2.8-5	7.6-9	4.3-9	8.5-10	.57
^{144}Ce	Lung	9.7-4	2.6-7	7.9-7	9.5-8	3.0
^{210}Po	Lung	3.1-2	8.4-6	1.3-5	2.1-6	1.6
^{223}Ra	Lung	2.6-2	7.0-6	1.7-5	2.0-6	2.4
^{224}Ra	Lung	8.8-3	2.4-6	6.6-6	7.9-7	2.7
^{226}Ra	Bone	1.2-1	3.2-5	7.6-6	2.1-6	.24
^{228}Ra	Lung	1.6-1	4.3-5	7.2-6	1.1-6	.17
^{227}Th	Lung	3.8-2	1.0-5	3.6-5	4.3-6	3.6
^{230}Th	Bone	2.3+0	6.2-4	2.2-3	8.6-5	3.6
^{232}Th	Bone	2.6+0	7.0-4	1.1-2	4.4-4	16.
^{234}Th	Lung	1.9-4	5.1-8	6.4-8	8.9-9	1.2
^{232}U	Lung	2.2-1	5.9-5	1.5-3	1.8-4	25.
^{233}U	Lung	5.3-2	1.4-5	3.0-4	3.6-5	21.
^{234}U	Lung	5.2-2	1.4-5	3.0-4	3.6-5	21.
^{235}U	Lung	4.9-2	1.3-5	2.8-4	3.3-5	22.
^{236}U	Lung	5.0-2	1.4-5	2.8-4	3.4-5	20.
^{238}U	Lung	4.6-2	1.2-5	2.7-4	3.2-5	22.
^{238}Pu	Bone	2.5+0	6.8-4	2.2-3	1.2-4	3.3
^{239}Pu	Bone	2.9+0	7.8-4	2.5-3	1.4-4	3.2
^{240}Pu	Bone	2.9+0	7.8-4	2.5-3	1.1-4	3.2
^{241}Pu	Bone	6.1-2	1.6-5	5.1-5	2.8-6	3.1

TABLE 2. (Continued)

Radionuclide	Critical Organs	Committed Dose Equivalent Factors ICRP 2 (NUREG-0172) (mrem/pCi)	ICRP 2 (NUREG-0172) (Sv/Bq)	ICRP 30 Critical Organ (Sv/Bq)	ICRP 30 Weighted Total Body (Sv/Bq)	Critical Organ Ratio[a] (ICRP 30 / NUREG-0172)
^{242}Pu	Bone	2.7+0	7.3-4	2.3-3	1.3-4	3.2
^{241}Am	Bone	9.4-1	2.5-4	2.5-3	1.4-4	9.8
^{243}Am	Bone	9.3-1	2.5-4	2.5-3	1.4-4	9.9
^{242}Cm	Lung	1.5-2	4.1-6	1.5-5	4.7-6	3.7
^{243}Cm	Bone	7.4-1	2.0-4	1.7-3	9.4-5	8.5
^{244}Cm	Bone	5.6-1	1.5-4	1.3-3	7.4-5	8.5
^{245}Cm	Bone	1.2+0	3.2-4	2.6-3	1.5-4	8.0
^{246}Cm	Bone	1.2+0	3.2-4	2.6-3	1.4-4	8.1
^{252}Cf	Bone	9.6-1	2.6-4	4.9-4	3.2-5	1.9

(a) The ratio shown is the ICRP Publication 30 committed dose equivalent factor divided by the NUREG-0172 committed dose equivalent factor.

(b) For the radionuclide shown, no data is listed for the critical organ in ICRP 30, thus a direct comparison is not possible.

result in inhalation committed dose equivalent factors that agree within about a factor of 5 of each other. A notable exception occurs for the isotopes of uranium where the Publication 30 factors are about 20 times higher than the Publication 2 factors. This increase is due in part to the application of the task group lung model, and in part to the use of updated metabolic data.

PRACTICAL IMPLICATIONS OF USING EITHER $(MPC)_a$ OR ALI

To correctly use either $(MPC)_a$ or ALI methods in radiation protection applications for workers, not only is a firm understanding of the method selected required, but also detailed exposure histories for each worker become essential. Both direct external exposure and potential internal exposure data must be included in these exposure histories. This means that radionuclide concentrations in the work place must be determined on a regular basis.

The ICRP emphasized in Publication 2 that the rate of intake of a radionuclide can be varied if the intake in any quarter is no greater than that resulting from a continuous exposure to the $(MPC)_a$ for 13 weeks. Thus, a detailed accounting of exposure can help determine when a worker has reached his exposure limit. Unfortunately, the concept of $(MPC)_a$ has been misused to imply concentrations that can never be exceeded under any circumstances. This practice may in theory reduce the need for detailed records, but it is in fact not consistent with the original intent of the ICRP.

To eliminate this misinterpretation, the ICRP eliminated MPC from its secondary limits and replaced it with ALI in Publication 26. Again, a detailed accounting of exposure histories can help determine when annual intakes reach the appropriate ALI values. While derived air concentrations (DAC) values are calculated, the ICRP emphasizes that they must always be used circumspectly since ALI values are always the overriding limit.

SUMMARY

The ICRP has defined primary and secondary limits on radiation exposure in an attempt to prevent or minimize somatic and genetic inquiries caused by radiation. For internal exposure, the total intake of radionuclides is the quantity of most concern in limiting exposures. $(MPC)_a$ values were originally

developed based on the intake associated with specific dose limits. However, MPC has been replaced by ALI as a secondary limit; thus, radionuclide intakes and not radionuclide concentrations in air have clearly become the limiting quantity. To be useful in limiting internal exposure, not only should the specific method selected (either MPC or ALI) be understood, but also adequate records of exposure should be maintained so that it can be determined when a worker has reached his exposure limit.

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