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Review of ICRP-60: Implications for Radioactive Waste Management*

Dr. Jas S. Devgun
Office of Waste Management Programs
Chemical Technology Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

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REVIEW OF ICRP-60:
IMPLICATIONS FOR RADIOACTIVE WASTE MANAGEMENT

Jas S. Devgun, Ph.D.

Office of Waste Management Programs
Chemical Technology Division
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439

1. INTRODUCTION

Radiation exposure has generally been managed based on exposure or dose limits. These limits have undergone revisions every decade or so as further information on the biological effects of various types of radiation became available. For example, in the early 1950's, for workers, a whole body dose limit of 3 mSv (0.3 rem) per week was being used in the United States until 1957 when the National Council on Radiation Protection and Measurements (NCRP) recommended a limit of 50 mSv (5 rem) per year. Currently, the U.S. Nuclear Regulatory Commission (NRC) specifies a whole body limit of 1.25 rem per calendar quarter (5 rem/y) (10 CFR 20).

The International Commission on Radiological Protection (ICRP) is the primary international body that provides recommendations in the radiological protection field. The commission operates independently of national authorities and its work is conducted through an international community of scientists. Its decisions and recommendations are held in high regard and form the basis of national radiation protection programs in various countries. Historically, the commission started as the International X-ray and Radium Protection Committee in 1928. In 1950, it was restructured and renamed to its present name. The commission works closely with a number of international bodies; its work also takes into account the progress made by major national organizations. The commission issued a major report called ICRP Publication No. 26 in 1977 (1); this report superseded the Commission's previous recommendations on radiation protection issued as Publication No. 1 in 1959 (2). Even though the Publication No. 26 was amended, clarified and extended in the subsequent Commission Statements, it has formed the primary guidance on the subject. These recommendations have generally been factored into radiation protection decisions by regulatory authorities in various countries and in setting exposure limits. In November 1990, the Commission adopted a new set of recommendations which were issued as

Publication No. 60 in March 1991 (3). This marked a major milestone in radiation protection guidelines as this is the first time that a comprehensive revision has been made since 1977 and a new system of radiological protection has been outlined. This system incorporates new radiobiological information and the current safety standard trends. The ICRP has also extended its advice to situations involving only a probability of exposure, such as radioactive waste disposal facilities.

Even though the regulatory dose and risk limits or constraints are set by individual national authorities, these new ICRP recommendations will have a significant impact on the radiation protection in all areas including radiation risk assessments for radioactive waste management and disposal, and remediation of radioactively contaminated sites. In this lecture, we will evaluate the implications of these new recommendations vis a vis radiation risk assessments for radioactive waste management and remediation of radioactive sites.

2. BASIS OF NEW ICRP RECOMMENDATIONS

Since the publication of 1977 recommendations, new information on biological effects of radiation has become available. Much of the new information on the risk of radiation-induced cancers has come from the continuing assessments of the Japanese atomic bomb survivors. New data have also become available from experiments with laboratory animals and cultured cells. In addition to its own assessments, the Commission relied heavily on the recent work and reports of two prominent committees - UNSCEAR and BEIR V. The first one is the United Nations Scientific Committee on the Effects of Atomic Radiation; the second is called the Committee on Biological Effects of Ionizing Radiation of the U.S. National Academy of Sciences. The UNSCEAR reports (4) and BEIR V Committee report (5) were the primary basis for reassessment of the 1977 recommendations. Another major report by the National Council on Radiation Protection and Measurements (NCRP) (6) has provided comprehensive information on the dose-response relationship and the influence of dose rate.

The ICRP-60 recommendations are based on the concept of "system of radiological protection" as compared to the 1977 "system of dose limitation". The conceptual framework of radiological protection introduces the ideas of source-related and individual-related assessments and it distinguishes between a "practice" which causes exposure, and "intervention" which decreases exposure. It also outlines a basic system of protection for occupational, medical and public exposures. The new recommendations cover not only the planned situations as in the past but also potential and pre-existing situations. Examples of the latter two are: probability of exposure in accidents and dispersal of radioactive materials; and radon in homes.

A few changes of nomenclature need to be noted before proceeding further. These are summarized here from Publication No. 60. The "non-stochastic" biological effects are now called "deterministic" effects which relate to loss of organ function. The "stochastic" effects can be somatic and hereditary. The Commission uses these quantities: equivalent dose, H_T, (previously, dose equivalent) for absorbed dose averaged over a tissue or organ (rather than a point); radiation weighing factor (W_R); effective dose (previously, effective dose equivalent) which represents weighted equivalent doses in all tissues and organs of the body (with W_T providing the tissue weighing factor for each tissue or organ); committed equivalent dose, $H_T(\tau)$ and committed effective dose $E_T(\tau)$ (related to integration over a specific time period τ); and collective equivalent dose S_T, and collective effective dose, S, for exposed populations. It should be noted that the new values of W_R and W_T have been adopted based on current radiobiological information. These values are listed in Table 1 and Table 2 reproduced here from ICRP-60 (the reader is referred to the ICRP-60 itself for additional notes/footnotes before applying these tables in any calculations).

Table 1. Radiation Weighting Factors

Type and Energy Range	Radiation Weighting Factor, W_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy <10 keV	5
10 keV to 100 keV	10
>100 keV to 2 MeV	20
>2 MeV to 20 MeV	10
>20 MeV	5
Protons, other than recoil protons, energy >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

(Source: ICRP-60, Table 1)

Table 2. Tissue Weighting Factors

Tissue or Organ	Tissue Weighting Factor, W_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

(Source: ICRP-60, Table 2)

In brief, if $D_{T,R}$ represents adsorbed dose for a tissue or organ T, due to radiation R:

$$H_T = \sum_R w_R D_{T,R}$$

$$E = \sum_T W_T H_T = \sum_T W_T \sum_R W_R D_{T,R}$$

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} H_T(t)\,dt$$

$$E(\tau) = \sum_T W_T H_T(\tau)$$

$$S_T = \sum_i \bar{H}_{T,i} N_i$$

$$S=\sum_i \bar{E}_i N_i$$

where N_i is the number of individuals in population group i receiving the mean organ equivalent dose, $\bar{H}_{T,i}$; and $\bar{E}_i$ is the mean effective dose to the population group i.

Primary data on deterministic effects in man came from the effects of atomic bombs in Hiroshima and Nagasaki. Recently much new information has also emerged from the accident at Chernobyl. For healthy individuals, the probability of deterministic effects is zero at doses up to some hundreds, and sometimes thousands, of mSv, depending on the tissue. However, above a threshold dose, the probability steeply approaches unity. The LD_{50} (in 60 days) due to bone marrow syndrome is about 3 - 5 Gy (300 - 500 rad). However, for low LET (linear energy transfer) radiation few tissues show clinically significant detrimental effects following acute absorbed doses of less than a few gray. For continued exposure over several years, severe effects are not likely in most tissues (except gonads, lens of the eye, and bone marrow) at annual doses of < 0.5 Gy.

For low LET radiation which is more of interest in remediation work and at radioactive disposal sites, stochastic effects are the main concern. The dose-response relationship is initially proportional, followed by a steeper rate of increase represented by a quadratic term ($E = \alpha D + \beta D^2$ where E is the effect and D is the dose), followed finally by a decreasing slope due to cell killing. The stochastic effects appear to have no threshold. Since the probability coefficients are based on atomic bomb survivor data where observations relate to high dose and high dose-rates, the Commission uses a factor called DDREF (Dose and Dose Rate Effectiveness Factor, called DREF by NCRP; see ref. 3 for details). The Commission recommends a value of 2 for DDREF i.e. probability of effects for low doses and low dose-rates are obtained by reducing by a factor of 2 the probability coefficients available for high doses and high dose-rates.

The system of protection advocated by the ICRP is based on:

- justification of practice,
- optimization of protection, and

• individual dose and risk limits.

This applies to proposed and continuing practices. For intervention the underlying principles are - *the proposed intervention should do more good than harm* i.e., reduction in detriment; and the optimization of intervention.

3. ICRP RECOMMENDATIONS AND THEIR IMPLICATIONS FOR RADIOACTIVE WASTE MANAGEMENT

In disposing radioactive waste in appropriate facilities, or remediating radioactive sites, radiation risk assessments must address the protection of workers (performing the cleanup or disposing radioactive waste) and the protection of the general public, especially those in proximity to the site.

The basic difference from past methodology will be to treat the system of radiation protection as a coherent system. An overall assessment of its effectiveness should be included in a systems analysis approach. While the dose limits provide useful quantities, mere compliance with dose limits is not considered sufficient demonstration of the satisfactory performance. The waste disposal practices, continuing or planned, should be justified to produce sufficient benefit to the exposed individuals or to the society. The likelihood of incurring exposures should be kept *as low as reasonably achievable* (ALARA), economic and social factors being taken into account. For occupational workers the exposure should be subject to dose limits and any potential exposures to workers or the public should be subject to risk limits.

For remediation of contaminated sites, the planning process generally involves comparisons of various alternatives. From the radiological protection point of view the detriment associated with each alternative should be compared with a no-action assessment of the radiation detriment since according to ICRP any proposed intervention (for example, decontaminating) should do more good than harm, i.e. result in net reduction in detriment. The form, scale, and duration of the intervention should also be optimized. The process of optimizing protection should be applied early in the design stage of the project.

The dose and risk limits apply to an individual to ensure protection from all sources. Radiation protection optimization process on the other hand is a source - based process. Thus, dose or risk constraints for an individual and related to a single source may need to be used. For waste disposal facilities pathways analysis can provide an estimation of exposure risk to an individual or the population in general.

In the 1977 recommendations, the ICRP specified an annual effective dose limit of 50 mSv (5 rem) for occupational exposure. The Commission used an underlying basis that the average fatal cancer risk in radiation work should not exceed the fatality risk in "safe" non-radiation occupations. The Commission used an assumption of average fatality rate of about 100 per million workers. It was also estimated that subgroups with high risk might run a risk 10 times higher than the average. Thus, the Commission assumed an annual fatality probability of 10^{-3} as a reference risk for setting the dose limit. The Commission no longer considers this method satisfactory. The 1990 recommendations adopt a more comprehensive and multi-attribute approach. In addition to the lifetime attributable probability of either death or severe heriditary conditions as the basis for judging the consequences for an exposure, other indices considered are: length of life lost due to an attributable death, reduction in life expectancy, the annual distribution of attributable probability of death, the increase in the age specific mortality rate, and morbidity due to non-fatal cancers and hereditary disorders.

In the ICRP approach, the dose limit represents a selected boundary between *"unacceptable"* and *"tolerable"* (exposures that are not unacceptable can be tolerable (not welcome but tolerated) or "acceptable"). In the multi-attribute analyses, the Commission used test values of annual effective dose limit at 10 mSv, 20 mSv, 30 mSv and 50 mSv. Two conclusions were drawn:

- the annual dose of 50 mSv (recommended in 1977) with a corresponding lifetime effective dose of 2.4 Sv (240 rem) is probably too high;

- the effective dose received in a full working life should be prevented from exceeding about 1 Sv (100 rem).

However, the Commission does not recommend the use of lifetime limits. The new recommended effective dose limit for occupational exposure is 20 mSv/y (2 rem/y), averaged over 5 years (100 mSv in 5 years) with a further provision that dose should not exceed 50 mSv in any single year. It should be noted that these limits apply to the sum of doses received from both external and internal exposures.

These recommendations will inevitably lead to a lowering of the regulatory dose limits for workers in future. It is also clear that in designing projects such as waste disposal facilities, the dose constraint for occupational workers should not exceed 20 mSv per year. Given the Commission's caution that it's dose limits be not seen as a target, and following the principle of ALARA, the remediation and waste disposal project planners will have to strive for lower occupational doses.

For an individual member of the public the Commission has re-confirmed an effective dose limit of 1 mSv/y (100 mrem/y) above background. However, in special circumstances, higher dose could be allowed in a single year, provided the average over 5 years does not exceed 1 mSv/y. The dose constraint for the facilities should thus be smaller than 1 mSv/y.

For comparison, the U.S. dose limits for public and occupational workers set by various agencies are discussed here. The U.S. Department of Energy (DOE) through its DOE Order 5400.5 (7) implements an effective dose limit of 1 mSv (100 mrem) per year as the primary standard for members of the public. However, it is also the policy of DOE to apply the ALARA process in radiation protection. For radiological workers, the DOE Order 5480.11 gives the exposure limits. In a recently issued Radiological Control Manual (DOE N 5480.6, June, 1992), following annual dose limits for workers are specified:

whole body (internal and external)	5 rem;
lens of eye	15 rem;
extremity (hands, arms, feet, legs)	50 rem;
skin	50 rem;
any organ or tissue (except eye)	50 rem.

However, it should be noted that DOE uses an Administrative Control Level of 2 rem per year (whole body) for all DOE activities. For a declared pregnant worker, the dose limit is 0.5 rem in nine months. However, DOE policy also states that after a worker declares pregnancy, mutually agreeable work assignments will be made available such that further occupational radiation exposure is unlikely. If the pregnant worker chooses to continue working as a radiological worker, efforts should be made to avoid exceeding 50 mrem per month to the pregnant worker.

The U.S. Nuclear Regulatory Commission (NRC) that regulates all civilian uses of radioactive materials as well as the operation of commercial nuclear reactors in the United States impements the standards for protection against radiation defined in Title 10, Part 20 of *Code of Federal Regulations*, 10 CFR 20. Permissible doses in restricted areas (occupational dose limits) in 10 CFR 20 are specified per quarter of a year as follows:

a)	whole body	1.25 rem;
b)	skin (whole body)	7.5 rem; and
c)	hand and forearms; feet and ankles	18.75 rem.

In applying the provisions of 10 CFR 20 (8) for the possession or use of radioactive materials, the NRC specifies an annual effective dose limit of 5 mSv (500 mrem) for unrestricted areas. However, for uranium fuel cycle operations it also specifies that provisions of 40 CFR 190 (9) apply which provide an annual effective dose limit of 0.25 mSv (25 mrem). The U.S. Environmental Protection Agency (EPA) uses a limiting criteria (40 CFR 61, ref. 9) of 0.1 mSv (10 mrem)/y for emission of radionuclides to ambient air. The NRC licensing requirements for land disposal of radioactive wastes (10 CFR 61, ref. 10) specify an effective (whole body) dose limit of 0.25 mSv (25 mrem)/y for a member of the public and a dose limit of 0.75 mSv (75 mrem) per year to the thyroid. The EPA's environmental protection standards for radioactive waste disposal include a groundwater protection requirement (40 CFR 191, ref. 9) that specifies an effective dose limit of 0.04 mSv (4 mrem) per year. As is evident, there is a need for general consistency between various national agencies and the international recommendations.

The ICRP also discussed an observation (11,12) in the United States,where chemical carcinogens exposing the public to an attributable lifetime cancer death probability of more than 4×10^{-3} seem to be regulated regardless of the cost. Even though there is no direct relevance to the radiation case, using a DDREF of 2 and the multiplicative model (see ref. 3), an annual dose of 1 mSv will cause an attributable lifetime fatality probability of 4×10^{-3}. It should be recognized, however, that the ICRP recommended effective dose limit of 1 mSv/y is not intended to apply to each practice but to total dose from all regulated practices. It's implications are clear. At a large contaminated site with multiple and diverse sources of contamination (such as buildings, soil, surface water, groundwater, air), the radiation risk assessment must address the system as a whole, not its various segments individually. However, it should be noted that the limit of 1 mSv/y applies to regulated practices; the natural background radiation including radon, which in the United States can result in annual doses to an individual ranging from 1 mSv to 3 mSv, are exempted. The background radiation dose may be undesirable but it is not a matter of choice. In risk assessments, the relative radiation risk from a cleanup project or a disposal facility in relation to the risk from background radiation at that site can provide useful comparisons in terms of whether the radiation risk situation of an individual is significantly changed.

For the lens of the eye and localized areas of skin, the Commission has provided separate dose limits because they will not be necessarily protected against deterministic effects by a limit on the effective dose. The Commission has retained an annual equivalent dose limit of 150 mSv (15 rem) for occupational workers for the lens of the eye (based on the estimated threshold of cataract at > 0.15 Sv). For the skin, the recommended annual limit (occupational) is 500 mSv (50 rem) averaged over any 1 cm^2. Because of a number of factors such as the length of total period of exposure and a wide range of sensitivity (3), the Commission adopted an arbitrary reduction factor of 10 for doses to the public in this case, giving an equivalent dose of 15 mSv for the lens and 50 mSv (averaged over 1 cm^2) for the skin. For certain remedial projects these doses may need to be considered.

A summary of the ICRP recommended dose limits is reproduced here in Table 3 from ICRP-60 (for application, the reader is referred to ICRP-60 and the related notes/footnotes).

Table 3. ICRP Recommended Dose Limits

	Dose Limit	
Application	Occupational	Public
Effective dose	20 mSv per year, average over defined periods of 5 years	1 mSv in a year
Annual equivalent dose in		
the lens of the eye	150 mSv	15 mSv
the skin	500 mSv	50 mSv
the hands and feet	500 mSv	--

(Source: ICRP-60, Table 6)

For internal exposure, the annual limits on intake (ALIs) will be based on a committed effective dose of 20 mSv and are being provided in Publication No. 61. For radon, based on several studies of underground miners (3), lung cancer probability coefficients are in the broad range of 1 - 4 x 10^{-4} /WLM. The Commission's Publication No. 50 (13) provides the ICRP calculated value of 1.5 x 10^{-4} /WLM. A Working Level Month (WLM) is exposure resulting from inhalation of air with a concentration of 1 WL of radon daughters for 170 working hours. The WL is defined as any combination of short-lived radon daughters in 1 liter of air that results in the ultimate release of 1.3 x 10^{5} MeV of potential alpha energy; this is approximately equal to the amount of energy emitted by the short-lived daughters in equilibrium with 100 pCi of radon.

It should also be noted that for occupational exposure of women who may be pregnant, the ICRP policy states that the methods of protection at work should provide a standard of protection for any conceptus broadly comparable with that provided the members of the general public. The Commission considers that its policy will be adequately applied if the mother is exposed, prior to a declaration of pregnancy, under the system of protection recommended by the Commission, including the recommended dose limits for occupational exposure. On this basis the Commission does not recommend a special occupational dose limit for women in general. Once pregnancy has been declared, the conceptus should be protected by applying a supplementary equivalent dose limit to the surface of the woman's abdomen of 2 mSv for the remainder of the pregnancy and by limiting intake of radionuclides to 1/20th of the ALI.

The ICRP has introduced a concept of "constraint" that may be applied to a single source; however, risk constraint is different from dose constraint and the two have to be treated independently. Application of the ICRP recommendations to waste disposal facilities presents unique difficulties because of the long periods of concern and the probabilistic nature of the problem. Release of radioactive material from a facility at present could lead to a maximum value of dose occurring far into the future as radionuclides are transported through the geosphere. Thus standards consisting solely of dose limits are difficult to apply and in its Publication No. 46, issued in 1985 (14), the Commission did recognize this. Since performance assessment of waste disposal facilities inherently requires risk assessment through pathways analysis for various release and exposure scenarios, use of risk constraints provides a more meaningful optimization of radiation protection because both the probability of an exposure and its magnitude can be included in the assessment.

In radioactive waste management in general and in operating a radioactive waste disposal facility, as well as, in decontaminating and remediating a radioactive site, the occupational and nonoccupational exposures must be below the dose limits, and dose constraint for each source will need to be considered, if an individual is exposed to more than one source. The result may be an establishment of dose constraints which will be fractions of the dose limit. This again underscores the importance of ALARA in the radiation protection optimization process.

In the previous recommendations (Publication No. 26). the Commission put forward an implied assumption of unacceptable risk limit of serious health effects of 10^{-5}. In the new recommendations the Commission discusses at length the concept and meaning of risk in general and finds the specific meanings of the word "risk" insufficient to describe radiation risks, risk situations, and risk acceptance. Because there is no consensus on what constitutes "unacceptable risk" or what the upper limit of risk is (which would not be acceptable even if it could not reasonably be further reduced), the new recommendations do not give a figure for risk limit.

Potential release of radionuclides from a radioactive waste facility may require intervention involving prevention (reducing the probability of sequence of events leading to exposure) and mitigation (limiting and reducing the exposure). Thus, risk assessments in design stages for various failure scenarios provide a valuable input. Engineered safety features can be designed into the facility. Also of relevance is the balancing of public and occupational exposures. For example, if there is a situation of release of waste to the environment it causes public exposure. However, remediation (and a reduction in public exposure) may result in increased occupational exposure. The Commission recommends optimization of protection using the combined collective effective dose from two types of exposure. Similarly, another situation may be when probability of failure of a facility (and the reduction in potential exposure) can be achieved only through inspection and at the expense of additional occupational exposure. The remedial actions can vary greatly in complexity and no general rules can be laid down. Each case has to be judged individually. In the Commissions's words the need for and the extent of remedial action has to be judged by comparing the benefit of the reduction in dose with the detriment of the remedial work.

In its advice on regulatory requirements, the Commission states that the regulatory agencies should be particularly concerned with public exposures because of the possibility of an individual being exposed to multiple sources. In its advice on management requirements, the commission has withdrawn its previous arbitrary dividing line between the controlled areas and supervised areas that ensured that dose to a worker in the supervised area was less than 3/10th of the occupational dose limit. It now leaves the designation of controlled and supervised areas to the operating management who may base their decision on the operational experience and judgement based on other factors. The Commission also no longer recommends a classification of two types of working conditions as it did previously.

Assessment of doses is fundamental to the practice of radiological protection. Estimation of potential dose, for example, from a potential release from a radioactive waste facility, involves use of models for radionuclide migration in the environment and models (for example, see ref. 15) for metabolic and dosimetric components. The parameters used should be as realistic as possible with an underlying recognition that the values should not underestimate the consequences of exposure. The exposure models that are used in the analysis should take into account the Commission's new radiation and tissue weighing factors.

The Commission recognized the need for exemption (of small sources that may give trivial dose or certain environmental situations) from regulatory control but does not explicitly state any limits in Publication No. 60. The reader is referred to Publication No. 55 (16).

4. CONCLUSIONS

The recent ICRP recommendations are based on a large amount of radiobiological information that has become available since 1977. They define new radiation and tissue weighing factors, specify new dose limits, discuss the concepts of risk at length, introduce a system of dose and risk constraints, and stress a system of radiological protection based on justification of practice, optimization of protection, and individual dose and risk limits. The Commission has made several changes to its 1977 recommendations. The Commission has extended its advice to situations where there is only a probability of exposure and the new recommendations should be applicable to all situations. In radioactive waste management and disposal or in remediation projects, one has to be aware of these new international developments. Indeed, national regulatory authorities are more responsive to ICRP recommendations and the emerging regulatory prescriptive limits are likely to be based on these recommendations. Finally, ALARA must be the mainstay of any radiation protection program.

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