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A Compilation of the Major Concepts and Quantities in Use by ICRP

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International Commission on Radiological Protection

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PREFACE

In 1980 the Commission asked Committee 4 to prepare a report compiling the concepts and quantities introduced in the new Recommendations (*ICRP Publication 26*) and other recent Publications.

The Commission wishes to thank G. A. M. Webb for his help in preparing the report.

The membership of ICRP Committee 4 at the time the report was adopted by the Commission was:

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1. INTRODUCTION

1. Throughout the more recent publications produced by the ICRP many new concepts and quantities have been introduced and used for particular purposes. Although these have generally been defined and explained in the appropriate publication it is not always possible to locate the definition readily, and, in particular, to be aware of a change in the intent or usage introduced in a later publication or explanatory statement. The intent of this compilation is to gather together the definitions and explanations of the more important concepts and quantities. New concepts or quantities are not introduced nor are changes made to definitions but expansion or clarification of the original explanations have been inserted in some instances. The primary source has been taken as *ICRP Publication 26*,[1] with the definitions of some basic quantities coming from recent ICRU publications.[2,3] The next most definitive source is statements made by the Commission, followed by other publications in the Annals, and, last, papers in the literature.

2. In order to provide some structure, the contents have been divided into two major sections, the first dealing with dosimetric quantities and the second with concepts and quantities related to the application of the ICRP system of dose limitation.[1] The dosimetric quantities have been further subdivided. The first section includes all those quantities used for expressing quantitatively the radiation exposure of individuals, whether identified or hypothetical persons. The second section contains those quantities used to express the radiation exposure of populations resulting from defined sources of exposure. This method of division is used because it fits best with the application of the quantities as part of the system of dose limitation.

2. DOSIMETRIC QUANTITIES

2.1. Quantities Concerned with Individuals

Absorbed dose

3. The fundamental assumption in describing in a quantitative way the interaction of radiation with matter is that the relevant measure of the interaction is the energy deposited per unit mass. This energy deposition, the *absorbed dose*, D, can result from all types of radiation, and is defined [2] by the relationship

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

where $\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to the matter in a volume element and $\mathrm{d}m$ is the mass of the matter in the volume element. The SI unit for absorbed dose is joule per kilogramme ($\mathrm{J\ kg^{-1}}$) and its special name is gray (Gy). The previous unit for absorbed dose was rad ($1\ \mathrm{rad} = 0.01\ \mathrm{J\ kg^{-1}}$).

4. If the energy imparted is determined in a small mass, random fluctuations of energy deposition can be important. The *specific energy* (imparted), z, defined by ICRU[2] as $z = \varepsilon/m$, where ε is the energy imparted to matter of mass m; z is therefore a stochastic quantity. D is the limit of the mean specific energy as m tends to zero. This aspect is of importance in microdosimetry but is not considered further here as it is not relevant to operational radiation protection. Several other quantities are of this nature and represent the expectation value of a stochastic quantity.

5. The quantity *exposure* has been used in the measurement of x and γ radiation. It is now passing out of use except as a quantity for reference standards, and is being replaced by *air kerma*, K, defined [2] by the relationship

$$K = \frac{dE_{tr}}{dm}$$

where dE_{tr} is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a material mass dm.

6. In studying the correlation between the energy deposition per unit mass in the human tissue and the resultant biological effects it soon becomes apparent that the biological effects do not depend solely on the energy deposition per unit mass, or absorbed dose, but also on other factors, notably the type of radiation. The correlation is also dependent on the particular type of biological effect and the distribution of the absorbed dose rate in time.

7. A direct and unequivocal correlation between irradiation and observed effect in a particular irradiated individual is only found for those consequences of high absorbed doses that have a threshold below which they do not occur (within normal individual tolerances). Such an effect is erythema (skin reddening); these effects have been called *non-stochastic* by the Commission. For the class of effects for which there is no evidence of a threshold dose, such as cancer induction, it is known that if a group of people are irradiated then a proportion will show the effect, but there is no way at present of predicting in which individuals it will be manifested. For any one individual, therefore, an increase in the irradiation can only be thought of as increasing the probability that the effect will occur. These effects have been called *stochastic* by the Commission. It is assumed for protection purposes that the risk of stochastic effects from irradiation of a tissue is directly proportional to the absorbed dose in the tissue, although various other *dose-response relationships* have been observed for particular effects under given experimental conditions.

Dose equivalent

8. There is a need in radiation protection for a well-defined numerical relationship between the assessed quantity describing the radiation exposure and its biological effects. The Commission has therefore used the quantity *dose equivalent*, H, which is intended to indicate sufficiently well the biological implications of radiation exposure at the levels of absorbed dose encountered in normal radiation protection. H is defined by

$$H = DQN$$

where Q is the quality factor and N is the product of all other modifying factors specified by the Commission. For the present the Commission has assigned a value of unity to N. Since both Q and N are dimensionless, the SI unit of dose equivalent is the same as for absorbed dose, namely J kg^{-1}, but to avoid confusion it has been given the special name sievert (Sv). The previous unit for dose equivalent was rem (1 rem = 0.01 J kg^{-1}).

9. The quality factor allows for the different effectiveness of different types of radiation and represents a considered judgment of the different values of relative biological effectiveness (see para. 12) for a given radiation for a range of biological endpoints. It is assumed to be dependent of the energy imparted per average track length in the tissue of interest and to be independent of the type of effect or endpoint. The value of Q has therefore been precisely defined by the Commission as a function of the *collision stopping power*, L_∞ in water at the point of interest. The Commission has specified the relationship at a number of values of L_∞ as shown in Table 1. Other values can be obtained by linear interpolation.

Table 1. Specified relationship between Q and L_∞

L_∞ in water (keV μm^{-1})	Q
$\leqslant 3.5$	1
7	2
23	5
53	10
$\geqslant 175$	20

10. If the absorbed dose is delivered by particles having a range of values of L_∞, an effective value $\bar{Q}$ at the point of interest can be calculated.[2] When the distribution of L_∞ is not known, it is permissible to use approximate values for $\bar{Q}$. The Commission has recommended such approximate values for all common types of ionizing radiation; these are given in Table 2.

Table 2. Recommended permissible approximation of $\bar{Q}$ for various types of radiation

Type of Radiation	Approximate value of $\bar{Q}$
X rays, γ rays and electrons	1
Thermal neutrons	2.3
Neutrons, protons and singly-charged particles of rest mass greater than one atomic mass unit of unknown energy	10
α particles and multiply-charged particles (and particles of unknown charge) of unknown energy	20

11. The quality factors are chosen to represent the effectiveness of different types of ionizing radiation in producing harmful effects at low doses. It is therefore important that the dose equivalent should not be used to assess all the likely consequences of accidental exposures in man which may involve severe non-stochastic effects. For that purpose, absorbed dose is the appropriate quantity after weighting for the *relative biological effectiveness* (RBE) of each type of radiation for the effects at high doses.

12. The relationship between Q and RBE is often misunderstood. RBE is defined as the ratio of the absorbed dose of a reference radiation to the absorbed dose of a test radiation to produce the same level of biological effect of the same extent and/or nature, other conditions being equal.[3] RBE can be used to obtain the biological response for a given effect from a given absorbed dose in the dose range specified. Since Q has been defined without reference to any particular biological endpoint, it therefore does not correspond to any particular value of RBE.

Effective dose equivalent

13. As mentioned earlier, the probability of occurrence of a stochastic effect in an organ or tissue is assumed to be proportional to the dose equivalent in the organ or tissue for radiation protection purposes. The constant of proportionality differs for the various tissues of the body, but in assessing health detriment the total risk is usually required. If the irradiation is uniform throughout all the tissues of the body then a single overall risk coefficient can be used, and assessment and comparisons can be made solely on the basis of the dose equivalent throughout the whole body. However, if the irradiation of different tissues is non-uniform—as is particularly

the case with irradiation from most internally deposited radionuclides—then a further quantity is necessary to represent the total risk.

14. The Commission has recommended a quantity for allowing for the different mortality risks associated with irradiation of different organs, together with a proportion of the hereditary effects. This quantity is defined by the sum:

$$\sum_T w_T H_T$$

where w_T is the weighting factor specified by the Commission to represent the proportion of the stochastic risk resulting from irradiation of tissue T to the total risk when the whole body is irradiated uniformly and H_T is the mean dose equivalent in tissue T. The Commission did not initially recommend a name for this sum but in a statement of clarification[4] suggested that it be called *effective dose equivalent*, H_E.

15. In assessing effective dose equivalent it does not matter in principle whether the dose equivalent in any particular tissue results from internal or external irradiation. All that is needed is to assess the dose equivalent in each tissue from all sources, multiply by the appropriate weighting factor and sum the results. If all the tissues in the body were uniformly irradiated then the result would be numerically equivalent to the whole body dose equivalent. Nonetheless, in many practical situations it is easier to assess separately the contributions from internal and external radiation.

16. The values of w_T recommended by the Commission are shown in Table 3;[1] they are considered by the Commission to be appropriate for protection for individuals of all ages and both sexes, i.e., for workers and members of the public. The value for gonads includes an allowance for serious hereditary effects, as expressed in the first two generations (i.e., the children and grandchildren of the irradiated individual). In practice the "remainder" organs or tissues are taken to be the five not specifically listed in Table 3 that receive the highest dose equivalents; a weighting factor w_T of 0.06 is applied to each of them, including the various portions of the gastro-intestinal tract, which are treated as separate organs. This procedure assigns the same risk coefficient to all organs or tissues not named in Table 3. This simplification affects only the method of calculating the effective dose equivalent. The definition itself covers all tissues.

17. There has been some confusion over whether skin should be treated as a "remainder tissue". The Commission in a statement of clarification[4] said that it did not intend the hands and forearms, the feet and ankles, the skin and the lens of the eye to be included in the "remainder", and that these tissues should therefore be excluded from the computation of effective dose equivalent. This exclusion may be taken to apply to the assessment of effective

Table 3. Weighting factors recommended by the Commission for calculation of effective dose equivalent

Organ or Tissue	Weighting Factor w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30

dose equivalent in the context of the protection of individuals. The definition of effective dose equivalent includes all tissues and the Commission statement refers to the exclusion of certain tissues from the computational procedure. The method for dealing with skin irradiation in the context of exposures of a population group is dealt with in para. 27.

18. The effective dose equivalent, while still a dosimetric quantity, is an indicator of the risk of death from somatic effects and the risk of hereditary effects in the first two generations, assumed to result from any irradiation, whether uniform or non-uniform, from both external and internal sources. It does not include hereditary effects in subsequent generations, nor any allowance for non-fatal somatic effects such as most cases of thyroid or skin cancer.

Committed dose equivalent

19. The absorbed dose from external irradiation is delivered at the same time as the tissue is exposed to the radiation field. However, for internal irradiation from incorporated radionuclides, the total absorbed dose will be spread out in time, being gradually delivered as the radionuclide decays. The time distribution of the absorbed dose rate will vary with the radionuclide, its form, the mode of intake and the tissue within which it is incorporated. To take account of this time distribution the Commission has defined the *committed dose equivalent*, which is the time integral of the dose-equivalent rate in a particular tissue that will be received by an individual following an intake of radioactive material into the body. The Commission has set the integration time as 50 years after the intake, taken to correspond to a working lifetime. The formal definition of committed dose equivalent is:

$$H_{50} = \int_{t_0}^{t_0 + 50y} \dot{H}(t)\, dt$$

for a single intake of activity at time t_0 where $\dot{H}(t)$ is the relevant dose-equivalent rate in an organ or tissue at time t.

20. Illustrative examples are given in Fig. 1 of the dose-equivalent rate in a tissue as a function of time after an intake of radionuclides with short and long effective half-lives. This shows the relationship between the dose-equivalent rate in the tissue and the committed dose equivalent which is the total shaded area.

Committed effective dose equivalent

21. If the committed dose equivalents to the individual tissues resulting from an intake are multiplied by the appropriate weighting factors w_T and then summed, the result will be the *committed effective dose equivalent*. To avoid ambiguity in defining the remainder tissues, the time integration should be carried out before selecting the relevant tissues for the summation. This quantity gives a measure of the total risk of specified somatic and hereditary effects to an average individual and his progeny from an intake of a radioactive material, including the risk from irradiation in subsequent years resulting from the intake.

Dose-equivalent index

22. The *dose-equivalent index*, H_I, at the point of interest, is defined as the maximum dose equivalent within a 30 cm diameter sphere, centred at the point, consisting of material equivalent to soft tissue with a density of 1 gm cm^{-3}. This quantity is referred to as the *unrestricted dose-equivalent index*. An important consequence of this definition is that H_I is not defined at distances closer than 15 cm from a surface or source. The maximum dose equivalent can occur at any point in the sphere and will only rarely occur at the centre.

23. The definition of the dose-equivalent index may be modified to make provisions for

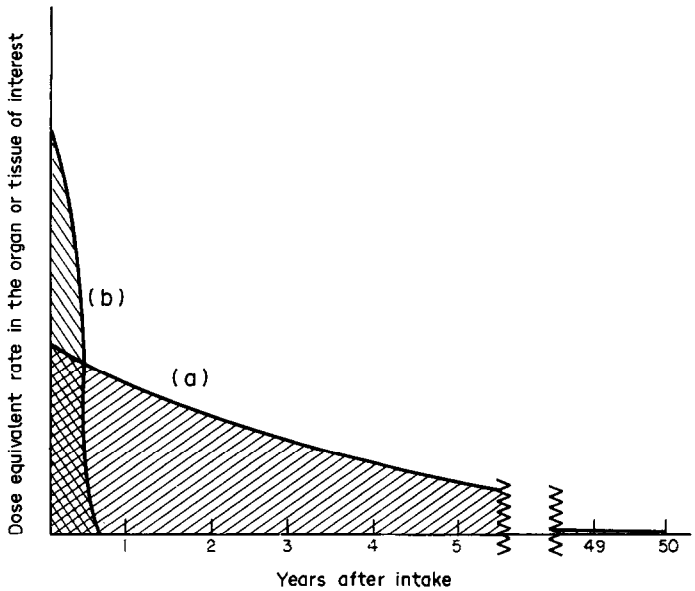

Fig. 1. Dose-equivalent rate in a given organ or tissue following an intake of a radionuclide with (a) long (b) short effective half-lives

radiation of low penetrating power. It is then convenient to consider separately the maximum dose equivalent in an inner core with a radius of 14 cm and the maximum dose equivalent in a surrounding shell of 1 cm thickness. These two maxima are termed the *deep* and *shallow dose-equivalent indices*, respectively, and their symbols are $H_{I,d}$ and $H_{I,s}$. They are referred to as *restricted dose-equivalent indices*. The larger of the two is the same as the unrestricted dose-equivalent index. It is recommended that the shallow dose-equivalent index shall not include the dose equivalent in the outer 0.07 mm of the 1 cm shell, since this is representative of the depth of the basal layer of the epidermis in areas where the skin is thin, and any radiation effects in the outer 0.07 mm are assumed to be negligible.

2.2. Quantities Concerned with Populations

24. These quantities relate, directly or indirectly, to sources of radiation exposure of populations and are nearly all collective quantities based on the individual quantities given earlier.

Collective dose equivalent

25. Given the assumption that effect is directly proportional to dose equivalent then it is useful to define a simple quantity to measure the total radiation exposure of a group of individuals. The quantity has been defined by the Commission as the *collective dose equivalent*, given by

$$S = \int_0^\infty HN(H)\,\mathrm{d}H$$

where $N(H)\,dH$ is the number of individuals receiving a dose equivalent between H and $H + dH$; or by

$$S = \sum_i \bar{H}_i N(\bar{H})_i$$

where $N(\bar{H})_i$ is the number of individuals in population subgroup i receiving an average dose equivalent of $\bar{H}_i$. The collective dose equivalent can be subdivided into components in which the individual doses lie within specified ranges.

Collective effective dose equivalent

26. If the dose-equivalent terms in the above definitions are replaced by effective dose equivalents then the resultant definitions give the *collective effective dose equivalent*, S_E.

27. As noted earlier, the protocol for calculation of H_E does not include any allowance for fatal cancers induced by irradiation of the skin or extremities. The Commission has, however, recommended[4] that, in the assessment of detriment from exposure to population groups, this should be taken into account by applying a risk factor in the region of 10^{-4} Sv^{-1} to the mean dose over the entire surface of the skin, which would correspond to a w_T of about 0.01. Since the quantity effective dose equivalent is uniquely defined using the weighting factors in Table 3, addition of a further factor would strictly require changes in the other factors to reduce the total to unity. In practice the addition of a factor of 0.01 for skin does not warrant any such change. If the circumstances are such that skin irradiation should be considered, then the sum of the collective effective dose equivalent plus the product of the mean skin dose and the additional weighting factor can be referred to as the *collective effective dose equivalent (including skin)* and defined each time it is used.

28. Neither the definition of collective dose equivalent nor of collective effective dose equivalent explicitly specifies the time over which the dose is delivered or whether the doses are to a single cohort which ages and eventually dies or to a succession of equivalent cohorts. This omission has lead to some confusion between the uses of, for example, the collective dose equivalent and the collective dose equivalent commitment, which is defined later. In many practical situations the collective dose equivalent is obtained by summing doses received over a specified time period, often 1 year. It would save confusion if the time period and population over which the collective dose equivalent is summed or integrated were explicitly specified where these are not obvious.

29. Even if the time period over which the collective dose equivalent is calculated is taken as 1 year, the collective committed effective dose equivalent from intakes of radionuclides in that year includes the 50 year integration of dose-equivalent rates in the relevant organs resulting from the intakes.

Per caput dose equivalent

30. If a population is uniformly irradiated and the population size increases then the collective dose equivalent will increase proportionally. It is sometimes useful, therefore, to express results in terms of dose equivalents to a hypothetical average individual. This quantity could be called the "average" dose equivalent but has become known as *per caput dose equivalent* because this specifies the quantity over which the averaging is conducted. Although it appears to be referring to an individual it is included under population-oriented quantities, because it only coincidentally represents the dose equivalent to an actual individual—it is the average of a range of actual dose equivalents. The *per caput effective dose equivalent* may also be defined by analogy with the section on effective dose equivalent.

31. The per caput dose equivalent may be obtained by dividing the collective dose equivalent over a given time in a specified population by the number of individuals in the population at the time, or, more directly, by calculating the average absorbed dose rate, or intake of radionuclides, from the source, and hence the average dose equivalent or committed dose equivalent. An example of the latter calculation would be the direct calculation of external dose equivalent due to global distribution of a given quantity of ^{85}Kr in the atmosphere via an intermediate calculation of the average krypton concentration in air.

32. When the future course of a given practice and characteristics of an exposed population can be predicted, the time variation of the per caput dose equivalent can also be found. This will be the variation with time of the average in the specified population and not of the actual dose equivalents in specific individuals. For example, the population of interest may be specified as children of average age 1 year and the per caput dose-equivalent rate from a discharge of a radionuclide calculated for a hundred years after discharge. This result then applies to a series of successive cohorts of children of ages averaging 1 year.

Dose-equivalent commitment

33. Given that it is possible to calculate the variation of per caput dose from a given practice as a function of time, it is also possible to integrate this function. The result is known as the *dose-equivalent commitment*, H_c, given by

$$H_c = \int_0^\infty \bar{\dot{H}}(t)\, dt$$

where $\bar{\dot{H}}(t)$ is the per caput dose-equivalent rate as a function of time. If the upper time limit of integration is infinity then the resultant quantity is known, without qualification, as the dose-equivalent commitment; if the integration is terminated at time T, then the resultant quantity is known as the *truncated* or *incomplete dose-equivalent commitment*, and time T should be specified.

34. The dose-equivalent commitment is not a directly useful quantity for justification or optimization studies because it relates to a hypothetical average entity and it is necessary to know the population size to obtain the presumed total number of health effects and hence the cost. It can however be shown that the maximum future per caput dose-equivalent rate per unit practice, if the practice continues at the same rate and all other relevant factors are assumed to remain constant, will, at equilibrium, be numerically equal to the dose-equivalent commitment per unit practice. This observation provides a simple means of estimating the maximum future annual per caput dose equivalent from a continued practice.

35. Similarly the maximum future per caput dose-equivalent rate per unit of a practice that continues at the same rate for T years and is then terminated is, under most circumstances, equal to the truncated per caput dose-equivalent commitment per unit practice. The same considerations apply when the dose equivalent is replaced by *effective dose-equivalent commitment*.

Collective effective dose equivalent

36. A given source or practice will give rise to a *collective effective dose-equivalent rate* which varies as a function of time. The total collective effective dose equivalent from the practice will be given by the integral of this. The formal definition of the *collective effective dose-equivalent commitment* is therefore

$$S_{E,c} = \int_0^\infty \dot{S}_E(t)\, dt$$

Although the collective effective dose equivalent in a year can sometimes be used in justification or optimization studies, the more useful quantity, particularly when considering the total health detriment, is the collective effective dose-equivalent commitment consequent upon a given decision or a total practice. However, the assumptions noted when discussing the effective dose equivalent must be borne in mind.

37. In principle the assessment of the future collective effective dose-equivalent rates can take into account predictions of future changes in environmental conditions. However, the difficulty of prediction normally leads to the assumption of the indefinite continuation of current conditions for parameters such as environmental transfer rates and human habits. While this may be reasonable for short periods, for some long-lived radionuclides calculations of the infinite commitment implies that current conditions apply for thousands or even millions of years into the future, an assumption which is open to criticism.

38. Although the mathematical computation of collective effective dose-equivalent commitment may appear simple, even for very long-lived radionuclides, the underlying assumptions must be borne in mind. There will often be merit in retaining an indication of the annual levels of individual effective dose equivalents and of the time variation of the collective effective dose-equivalent rate, as additional data on which to base decisions.

39. It is possible to terminate the integration at time, T, after the start of the practice which results in an *incomplete or truncated collective effective dose-equivalent commitment*. The decision to use this quantity in justification or optimization, rather than the infinite integral, cannot always be justified by reference to the length of time over which the practice is assumed to persist because there need be no relationship between this and time T. However, on many occasions what will be required is a comparison of the short-term effects of alternative decisions, e.g., in waste treatment options, which would be highlighted by use of the truncated quantity, but submerged in the infinite integral.

3. CONCEPTS AND QUANTITIES RELATED TO THE SYSTEM OF DOSE LIMITATION

40. The Commission has summarized its recommended basic system of dose limitation in terms of three components which are necessarily interrelated.[1]

1. No practice shall be adopted unless its introduction produces a positive net benefit.
2. All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.
3. The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

These three components are identified by the Commission by the abbreviated terms:

1. The *justification* of the practice.
2. The *optimization* of radiation protection.
3. The *dose limits* for individuals.

3.1. Justification and Optimization

Justification

41. The wording of this principle in referring to a "positive net benefit" invokes the idea of cost–benefit analysis (dealt with in detail later in this section), and the further explanation[1]

states that ideally the acceptability of a proposed operation or practice involving exposure to radiation should be determined by cost–benefit analysis. It is noted, however, that the choice between practices will depend on many factors, only some of which will be associated with radiation protection. It is now recognized that only some of the relevant factors can be encompassed at present within the techniques of cost–benefit analysis so that more general decision-making methodologies would need to be applied to decisions on the justification of practices. In the very few cases where decisions on justification are called for, the principle should be regarded in a rather general way as a sensible statement that all the merits and all the harm associated with the practice under consideration and the possible alternatives should be taken into account in reaching the decision.

Optimization

42. It is now clear that "*keeping all exposures as low as reasonably achievable*", "*optimization of protection*" and "*ALARA*" are identical concepts within the ICRP system,[5] even though the acronym "ALARA" is not used by the Commission.

43. A wide range of techniques is available to optimize radiation protection. Some of these techniques are drawn from operational research, some from economics and some from engineering. The techniques available include, but are not confined to, procedures based on cost–benefit analysis, although it is these procedures that have been discussed in detail in the ICRP report on optimization of protection.[6] It is important to recognize that other techniques, some quantitative, some more qualitative, may also be used in the optimization of radiation protection.

Detriment

44. In order to quantify the deleterious effects of radiation, the Commission has introduced the concepts of *risk* and *detriment*. The risk associated with a given dose is the probability that a given individual will incur a particular radiation-induced effect as a result of the dose received. The detriment, on the other hand, is defined as the mathematical expectation of the amount of harm in the exposed group of people, taking into account both the probability and the severity of the different possible harmful effects. Harmful effects include the stochastic and non-stochastic effects (adding up to what is sometimes called the *objective health detriment*) as well as the concern and anxiety of the individuals at risk and any adverse consequence for the comfort of these individuals due to restrictions imposed as a result of radiation exposures. At exposure levels below the dose limits, as encountered in normal situations, non-stochastic effects are precluded. The stochastic component of the health detriment is deemed to be proportional to the collective effective dose equivalent.

45. The concern and anxiety of the individuals exposed to radiation results from many factors. One of these factors is the level of risk and the associated attitude to risk. Under the assumptions made by the Commission in its recommendations, the level of risk is proportional to the individual effective dose equivalent. The attitude toward risk, on the other hand, cannot be taken to be proportional to risk at all risk levels. It may also be affected by the magnitude of the dose equivalent received in relation to the dose-equivalent limits. As a result, the contribution to this component of the detriment from each exposed individual is a function (not necessarily linear and not necessarily the same for all exposed groups) of the effective dose equivalent to that individual.

46. The assessment of the objective health detriment via the collective effective dose equivalent, does not include the hereditary contribution to the detriment of generations

subsequent to the second generation nor the contribution from non-fatal malignancies. Furthermore, the actual risk per unit effective dose equivalent depends on sex, age and other factors. The possible influence of these omissions and other effects on the optimization of radiation protection was reviewed by the Commission[7] which noted that the addition of the future genetic harm in the case of uniform whole body exposure would add a further risk of 0.4 10^{-2} Sv^{-1} in the case of the public, or rather less in the case of the average worker, to the total assumed risk of 1.65 10^{-2} Sv^{-1}; i.e., it would increase the total detriment by at most 24%. In the less likely case that the gonads received the dominating dose, the genetic harm would be twice that implied by the effective dose equivalent alone.

47. The weight of the additional detriment attributed to non-lethal cancer would depend upon the weight to be attached to a given length of time lost from normal health (during illness prior to cure) relative to an equal period of life lost as a result of death from cancer. If that relative weight is taken to be 0.1[8] the addition of the detriment due to non-lethal cancer and the induction of benign tumours would only increase the total non-genetic detriment by 2% in the case of uniform whole-body exposure. If organs such as thyroid and skin, for which cancers have a low fatality rate, are irradiated alone, and the relative weight is taken to be as high as 0.5, the total detriment will approach about twice that implied by the use of the effective dose equivalent alone. However, in most cases of external exposure, or of exposure to mixtures of radionuclides, the Commission concluded that use of the effective dose equivalent would not significantly underestimate the total detriment.

Cost-benefit analysis

48. The basic idea underlying the application of cost-benefit analysis techniques in the optimization of protection is very simple: an option is selected if the net benefit from that option exceeds the net benefit from other available options. Searching for the option displaying the maximum net benefit requires an interplay between the *cost of protection* and the *cost of the detriment*, each of which is a function of the level of protection, such that the sum of the two costs is minimized. If the level of protection is represented by w, then this balance is achieved when

$$X(w) + Y(w) = \text{minimum}$$

where X is the cost of protection
and Y is the cost of detriment.

It is also possible to express the condition in differential form taking w as the independent variable and w_o as the mathematical "optimum" to give

$$\left(\frac{dX}{dw}\right)_{w_o} = -\left(\frac{dY}{dw}\right)_{w_o}$$

This formulation is that referred to as *differential cost-benefit analysis*. If it is assumed that the level of protection can be fully represented by the collective effective dose equivalent, then the w could be replaced by S_E in the above expression.

49. It is not necessary to consider all sets of X and Y which may fulfil the requirements of the optimization equations. The acceptable solutions are obtained subject to further restrictions imposed through *constraining functions* and *limit equations*. Constraining functions express some interrelationship between the variables X and Y stemming from basic factors such as the laws of physics or impositions on the system such as the value assigned to the detriment. Although the dose-equivalent limits serve as a constraint on the system these are not formally imposed by a constraining function, but by a limit equation. This can often be expressed as a

simple inequality of the form:

$$H_E(w) \leqslant H_{E,l}$$

where $H_{E,l}$ is the appropriate limit on the individual effective dose equivalent, and $H_E(w)$ is the effective dose equivalent to the most exposed individual at the level of protection w.

50. The appropriate limit may be the annual effective dose-equivalent limit in a case where the source can be treated independently from all other sources; this could be because it dominates the exposure to a particular group of people or because the dose distribution is geographically localized. In many cases, however, it will be necessary to establish an *upper bound* on the basis of the highest risk that is considered acceptable to individuals from the source being considered, making explicit allowance for risks from other sources of radiation exposure. The purpose of the *source upper bound* is to act as a constraint on the optimization of that source to ensure that the exposure of any individual will remain below the relevant dose-equivalent limit even if he is exposed to several sources.[9] The upper bound for a single artificial source is therefore set at some fraction of the annual dose-equivalent limit. The concept of an upper bound has also been applied by the Commission to the control of exposure from natural sources, to which the dose-equivalent limits do not apply.[9]

51. Options for protection are sometimes compared using *cost–effectiveness analysis*. In this procedure the cost of protection and the level of residual detriment are assessed but do not have to be expressed in the same units. The most cost-effective option is that which achieves the largest reduction in detriment for a fixed cost or, alternatively, the least costly means of achieving a target level of detriment. There is no way of telling from such an analysis whether the most cost-effective option is the optimum as defined above.

Cost of protection

52. The evaluation of the cost of protection may sometimes prove to be quite complex. For example, if the selection of a given level of protection involves manufacturing and installing a protection system and ensuring its operation, the costs should, in principle, include not only the expenditure incurred in these operations, but also those that are incurred by the procurement of basic materials or components for the system, together with the cost borne by society related to the harm associated with all these operations. However, it can usually be assumed that all these costs have been incorporated in the monetary cost of procurement, installation and operation of the system.

53. The monetary valuation of the protection cost is based on conventional economic techniques that take account of the actual expenses and their distribution in time. These techniques are discussed in the technical sections of the report on optimization[6] and are described in detail in the available literature on accounting procedures. The two most commonly applied procedures are *present worth evaluations* and *capitalized* or *annualized cost estimates*. Both of these take into account the initial capital expenditures and the operating or running costs over the lifetime of the installation with allowance for *discounting* of costs incurred in the future for comparison with costs incurred at the start.

Cost of detriment

54. The assessment of the cost of detriment can be controversial and involves implicit or explicit judgments on values of health (and therefore of life) and in some cases of non-health harm. The cost of the detriment, Y, can conceptually be divided into components, which can be treated separately

$$Y = Y_H + Y_1 + Y_2 \ldots\ldots$$

where Y_H is the cost of the objective health component of the detriment; and Y_1, Y_2 ..... are the costs of the various other significant components of the detriment.

55. The valuation of the objective health detriment can be viewed as involving the reduction of actual resource costs and of effects on human health to common dimensions, and their subsequent aggregation and comparison on that basis. This procedure has been criticized because it implicitly places monetary values on human life, health and safety. However, such criticism fails to acknowledge the reality of the situation, which is that the resources available to society are finite and that safety improvements typically commit some of these finite resources which will not be available in the future for other purposes. Any decision on a particular improvement in safety necessarily involves a relative valuation of health. The fact that, in cost-benefit analysis, this relative valuation is typically conducted in monetary terms is merely a matter of convenience. Any other common measure of value would, in principle, do equally well.

56. When other components of radiation detriment are taken into account, their costs should be added to the cost of the objective health detriment. If the other components of the detriment taken together depend on individual doses, the cost of the detriment can be expressed in the following general form:

$$Y = \alpha S + \beta \sum_j N_j f_j (H_j)$$

where

α is a dimensional constant expressing the cost assigned to the unit collective dose equivalent for radiation protection purposes.

β is the monetary cost assigned by the decision-maker to a unit of the other components of the detriment;

f_j is a function of individual dose equivalent, which would depend on risk-aversion attitudes and national or managerial regulations; and,

H_j is the per caput dose equivalent to the N_j individuals in the jth group.

57. The first term in the expression for Y is only related to the collective dose. The second term reflects the possibility that in some complex situations it may be desirable to add the costs associated with additional components of detriment to take account of non-objective features and of non-health detriments which may not be proportional to the collective dose. In the special case where the additional components of detriment are proportional to components of the collective dose then the second term could be expressed as

$$\sum_j \beta_j N_j H_j$$

where β_j is the monetary cost assigned by the decision-maker to the unit of the collective dose equivalent delivered to the jth group.

58. The assignment of a numerical minimum international value for α is being addressed by the IAEA. The choice of national values for α and β is a matter for appropriate national authorities. Care should be exercised in disaggregating values which include α and β terms, and in particular it should be understood that values referred to in the literature loosely as "values of α" or "the cost of the man-sievert" may contain an implicit β term.

59. Methods of comparing costs at different times often use techniques such as *discounting* which has been referred to in assessing the costs of protection. The decision whether to discount the cost of future detriment is more controversial, partly because the time span over which the detriment is spread is often very much greater than in the case of the costs of protection. It must

be emphasized that the detriment itself is not to be discounted; the quantity to which the technique can be applied is the cost assigned to the detriment.

3.2. Dose Limits

Dose-equivalent limits

60. The Commission recommends annual dose-equivalent limits. These limits relate to the dose equivalent received by an individual as a result of each of several exposure conditions. For example, a worker may be occupationally exposed and also exposed as a member of the public. The dose limits apply to each category of exposure separately. In practice, it is convenient to refer to the limits as applying to workers or to members of the public, but these expressions should be interpreted as applying to the categories of exposure, thus avoiding the need to categorize individuals. To improve clarity, the Commission, in its explanatory statement[4] noted that the dose-equivalent limits for workers are intended to apply to the sum of the dose equivalent resulting from external exposure during one year and the committed effective dose equivalent from that year's intake of radionuclides. Similar principles apply to the dose-equivalent limits for members of the public. The limits apply to the sum of internal and external exposures, but in practice it is often convenient to evaluate these separately and then sum them.

61. The dose equivalent from external radiation is delivered at the same time as the radiation is received, so the limit for a given year applies to the external radiation received during that year. The dose equivalent from an intake of radioactive materials may be spread over future years, and in this case it is the committed effective dose equivalent that must be compared with the limit.

62. Although the secondary limits referred to later, notably annual limits on intake and derived limits, are calculated directly from the dose-equivalent limits, these will only be of direct use when the exposures of individuals from all sources are being considered or when one source can be treated independently. In most practical situations the dose-equivalent limit will be replaced by the source upper bound, which will be a fraction of the limit for artificial sources. In this situation similar fractions of the secondary limits will also be of more direct use.

Annual limits on intake for workers

63. In order to simplify the comparison of the committed effective dose equivalent from intakes with the dose-equivalent limits it is convenient to calculate secondary limits for individual radionuclides giving the maximum intake in a year directly. The secondary limits are known as *annual limits on intake* (ALI); they normally correspond to a committed effective dose equivalent from an intake of a given radionuclide equal to the appropriate dose-equivalent limit for workers.[10] Restriction of the intake in each year to less than the ALI therefore ensures that the maximum annual dose equivalent from that radionuclide will always be less than the dose-equivalent limit even if intake occurred every year for 50 years.

64. It is worth emphasizing that the underlying objective remains the limitation of the risk to which a worker is committed by each year of operation, no credit being taken for earlier years if these have committed lower risks or for future years in the expectation of improved conditions of exposure. The Commission recognizes that there are practical difficulties in using monitoring results to estimate annual intakes of some materials, notably plutonium, but it believes that these difficulties can be overcome and therefore that their existence does not invalidate the above conclusions.[15] This has potentially important implications both for monitoring and control of workers likely to acquire internal contamination and for dose record-keeping; these are discussed in *ICRP Publication 35*.[11]

65. In practice, when actual dose equivalents are compared with the limit these can be replaced by secondary quantities so that:

$$\frac{H_{I,d}}{H_{E,l}} + \sum_j \frac{I_j}{I_{j,l}} \leqslant 1 \text{ and } \frac{H_{I,s}}{H_{sk,l}} \leqslant 1$$

where $H_{E,l}$ is the annual effective dose-equivalent limit
I_j is the intake during the year of nuclide j
$I_{j,l}$ is the annual limit on intake for the nuclide j
$H_{sk,l}$ is the annual limit on the dose equivalent in the skin.

66. It is noted[11] that compliance with both the limits for external exposure will, in most practical situations, afford compliance with the annual dose-equivalent limit for the lens of the eye, which was reduced to 0.15 Sv in 1980.[7]

67. Although the procedure appears to restrict the use of the effective dose-equivalent concept to internal emitters via the use of ALIs, this is only for practical convenience. Other field quantities could also be used in place of the dose-equivalent index as an adequate measure of the effective dose equivalent from external irradition. There is one other restriction on the value of ALIs not yet mentioned. The Commission has imposed an upper limit on the annual dose equivalent in any tissue to prevent non-stochastic effects. In many cases, this, rather than the stochastic limits represented by the w_T values, determines the ALI for particular radionuclides. It should be noted however that in certain circumstances the inequalities described above may be more restrictive than control on the basis of comparison of the committed effective dose equivalent and the individual organ or tissue doses with the appropriate dose-equivalent limit, if one or more of the ALIs are determined by non-stochastic effects.[10]

68. In some situations *derived air concentrations* (DAC) are of practical use. These are obtained by dividing the ALI by the volume of air inhaled by *Reference Man*[12] in a working year of 2000 hours at a breathing rate of 1.2 m^3h^{-1}. The Commission has drawn attention recently to the fact that for short-lived nuclides there is an important additional contribution from external irradiation.[13] This may be greater than that due to inhalation and should be assessed as part of the external irradiation. DACs are also derived, where appropriate, for submersion of Reference Man in a cloud of radioactive inert gas or in a cloud of elemental tritium.[10]

Annual limits on intakes for members of the public

69. The same principles that apply to the calculation and use of secondary limits such as ALIs for workers apply also to members of the public. The Commission has recently issued a statement[13] discussing the difficulties that arise in practice from differences in body size and metabolism, especially of infants and children, as well as from differences in chemical form of radionuclides in the public environment. For adult members of the public the duration of potential exposure is comparable with the 50 years used as the integration time in calculating committed dose equivalents, and their metabolic and biological parameters will be adequately represented by those of Reference Man. The Commission has also indicated that it regards the weighting factors used in the derivation of the effective dose equivalent to be a sufficiently good approximation for members of the public as well as workers. Since the non-stochastic limits have also been divided by a factor of ten, apart from that for the lens of the eye which is not relevant to these calculations, ALIs for adult members of the public, for radionuclides in the same physico-chemical form as those found in the workplace, can be obtained by dividing the ALI figures for workers[10] by 10.

70. When the group of the public under consideration differs substantially in biological characteristics from adult Reference Man, as is the case with infants and young children, then the Commission recommends that account must be taken of differences in organ size and metabolic characteristics. An integrating time of 50 years is used in computing the committed dose equivalent in an organ of a worker. The Commission believes[13] that this period is also adequate for a member of the public since the correction factor would be no more than 70/50. Exceptionally, the more complicated, but more rigorous, approach of integrating from the age of intake up to the age of, say, 70 years could be applied. The proper procedure is to carry out such calculations to derive values of committed dose equivalent per unit intake for population groups markedly different from adults, particularly infants and children, using the same principles as Committee 2 used to calculate the values for workers, but applying the appropriate biological parameters and taking account of the physico-chemical forms of radionuclides likely to be encountered in the public environment.

Critical groups

71. The dose limits for members of the public are intended to be applied to the average effective dose equivalents to the members of the *critical group*. This group should be representative of those individuals in the population expected to receive the highest dose equivalent. The group should be small enough to be relatively homogeneous with respect to age, diet and those aspects of situation and behaviour that affect the doses received. The group may comprise existing persons who are exposed at a higher level than the general population or it may be a future group of persons who may be expected to be exposed at higher levels. The concept of a critical group is discussed further in another report.[14]

72. In deciding which of the more highly exposed groups constitutes the critical group it is necessary to investigate the pathways of exposure from the radionuclides under consideration. The depth of investigation will depend on how large are the estimated effective dose equivalents. For estimated effective dose equivalents of more than a few percent of the dose limits quite detailed habit surveys of potential critical groups are likely to be required. The pathway leading to exposure of the critical group is the *critical pathway* and the radionuclide giving the highest dose is the *critical nuclide.*

73. The selection of an appropriate critical group is not always easy. One of the key determinants in the selection is the number of individuals in the critical group. It is clearly stated that the dose limits apply to the mean dose equivalent in a relatively homogenous group. Usually the critical group would not consist of a single individual nor will it usually be very large or homogeneity will be lost. The size of most critical groups will therefore be up to a few tens of persons.[14]

74. Just as it is necessary to vary the metabolic parameters when calculating ALIs for members of the public who are not adults, so it is necessary to adopt appropriate values for intakes by infants and children when these constitute the critical group.

Derived limits

75. In many practical circumstances it is difficult to relate measured quantities directly to the dose limits or even to secondary limits. It is therefore useful to provide limits associated with the quantities actually measured, for example, levels of contamination in environmental materials. When these limits are related to the basic limits by a defined model and are intended to reflect the basic limits, they are called *derived limits*. When they are related to the source upper bound in the same way they are called *derived upper bounds.*

76. The accuracy of the link between derived limits and basic limits, or between source upper

bounds and derived upper bounds, depends on the realism of the model used in the derivation. A derived limit may be calculated for a very specific and well characterized situation, in which case it will correspond closely to the dose-equivalent limit, or the model may be very generalized in a conservative manner, in which case the relationship to the dose-equivalent limit is less direct. The general limit usually contains more conservatism than one calculated for specific circumstances. Derived limits should only be used for the circumstances for which they were calculated.

77. The Commission recommends an annual effective dose-equivalent limit of 5 mSv for individual members of the public, noting that a change in the upper limit would not be of the same importance from the radiation protection point of view as the rigorous application of the principle of keeping all doses as low as is reasonably achievable. Nonetheless, it suggests that, in the rare cases where the dose equivalents to a few individuals in critical groups are actually found to be received at high rates over prolonged periods, it would be prudent to take measures to restrict their lifetime dose equivalent to a value that would correspond to 1 mSv per year of life-long whole body exposure.

Authorized limits

78. Although the derived limits or derived upper bounds provide a means of comparison with the dose limits or source upper bounds, it is normal for practical working limits on the dose-equivalent rate, the release rate of radionuclides or the concentrations in environmental materials, to be set by appropriate national authorities or managements. These are known as *authorized limits*. They should, in general, be below derived limits or derived upper bounds though, exceptionally, they may be equal to them. Authorized limits for workers may be general and of wide application or may apply only to well-defined local circumstances. Authorized limits for the public are generally applied to control the doses to members of the critical group. They will however have been selected after considering the result of an optimization study constrained by the appropriate source upper bound or, exceptionally, by the dose-equivalent limits. The authorized limit will often be somewhat higher than the result of the optimization to allow for uncertainty in the procedure and to provide operational flexibility.

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