Principles for Establishing Limits for the Release of Radioactive Materials into the Environment
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FOR THE RELEASE   
OF RADIOACTIVE MATERIALS   
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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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The expansion in the generation of nuclear power has prompted the Agency to develop a more comprehensive approach for setting limits to the release of radioactive substances into the environment. The Agency's policy is to conform with the dose limitation system of the ICRP. That system recommends that individual dose limits should not be exceeded, and that doses be kept as far below these limits as is reasonably achievable, taking social and economic considerations into account. The second of these recommendations, usually referred to as the optimization of radiological protection, requires the use of differential cost-benefit analysis.

It is recognized that at present many decisions are made using other procedures, such as, for example, the application of safety factors to release limits derived only from the dose limits. The Agency, however, believes that the explicit use of the full system of dose limitation, which includes optimization, is a more rational approach to the establishment of release limits.

This report provides a basic consideration of concepts and principles for use by national authorities in setting limits for planned releases of radioactive material. The report stems from the work of Advisory Groups; the last meeting, chaired by Professor Bo Lindell, took place in Vienna on 17–21 May 1976.

The Agency intends to publish a series of complementary documents on the application of these principles in various practical situations.
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## CONTENTS

### CHAPTER I. GENERAL CONCEPTS ................................................................. 1

**Introduction** .............................................................................................. 1

Objectives of radiation protection in relation to environmental releases of radioactivity .......................................... 2

Dose limits ................................................................................................... 4

Collective dose and detriment .................................................................. 6

Dose commitment and collective dose commitment ...................... 10

Collective dose commitments from future sources ........................... 11

Models relating radiation discharges, environmental levels and doses ..................................................................................... 13

Derived limits.................................................................................................. 16

Discharge limits and operational limits .............................................. 16

References to Chapter I ........................................................................... 18

### CHAPTER II. ASSESSMENT OF DOSE TO THE CRITICAL GROUP ................................................................. 21

**Aims** ............................................................................................................ 21

Critical pathway analysis .......................................................................... 22

Information necessary for the model ..................................................... 24

Effluent composition ............................................................................... 24

Dilution and dispersion in the receiving medium ................................ 25

Transfer to critical environmental materials ........................................ 26

Environmental habits survey .................................................................... 27

Calculation of dose .................................................................................... 28

Identification of critical group ............................................................... 29
APPENDIX 1. EXPLANATION AND APPLICATION
OF THE CONCEPT OF COLLECTIVE DOSE COMMITMENT ... 69
Integration of collective dose rate in space .......................... 70
Integration of collective dose rate in time .......................... 72

APPENDIX 2. DISCHARGE LIMITATIONS BASED ON
CONCENTRATION INDICES ...................................................... 85
Specific activity approach .................................................. 86
Total systems analysis approach ........................................... 87

List of Participants ................................................................. 89
Chapter I

GENERAL CONCEPTS

INTRODUCTION

1—1. In the fuel cycle of the nuclear power industry, and to a minor extent in the use of by-products of nuclear activities, radioactive wastes are produced. As is well known, almost all of the activity of these wastes is contained and not released to the environment except for a minor fraction, the release of which should comply with the relevant national or local requirements in radiation safety.

1—2. It has often been considered sufficient to limit the release of radioactive material to the environment by limiting the concentrations of the various radionuclides in air and water effluents, the limit usually being a fraction of the Maximum Permissible Concentration (MPC) recommended by the ICRP [1] in 1959 for application in radiological work. Obviously such limits in themselves would not prevent substantial amounts of radioactive material from reaching the environment if the effluent rates were high, nor would they assure that ecological concentration processes might not cause high concentrations in certain environmental materials resulting in unexpectedly high doses in members of the public. In many cases these eventualities were taken into account either explicitly or by introducing safety factors in the concentration limits or sometimes in the amounts allowed to be released. The present trend of sophistication in radiation protection philosophies, however, has a corresponding influence on waste disposal policies, in particular relating to the limitation of environmental releases and to the assessment of radiological significance of such releases. Therefore, new principles have been, and continue to be, developed [2—5].

1 The term dose as used in this report means dose equivalent unless qualified otherwise.
OBJECTIVES OF RADIATION PROTECTION IN RELATION TO ENVIRONMENTAL RELEASES OF RADIOACTIVITY

I–3. The basic objectives of radiation protection are to prevent the occurrence of acute effects and to limit the probabilities of occurrence of late somatic and genetic effects to levels deemed to be acceptable. The first of these objectives is easily met since acute effects occur only subsequent to large doses at high dose rates. The second objective relates to much more complicated problems, mainly due to the absence of human data at the levels of exposure which are currently permitted. It has been the normal practice in radiation protection to assume that a non-threshold direct proportionality relationship exists between the dose and the probability of such late effects as the induction of malignancies and deleterious hereditary effects. Furthermore, it is assumed that the risk per unit dose deduced from observations at high doses and dose rates apply to the low dose range and low dose rates relevant for radiation protection. Thus, for small dose increments above natural background, it may be assumed as a first approximation that the increment of risk is proportional to the increment of dose (see para.I–18). This assumption may, however, not necessarily form the most appropriate basis for estimates of the actual risk associated with low dose [1,6].

I–4. An implicit consequence of these assumptions is that no radiation exposure can be assumed to be absolutely safe. The main issue is therefore the acceptability of the presumed potential risks, in relation to both the acceptability of other risks by society and the benefits expected by society from the operations causing the exposure.

I–5. The basic principles of radiation protection are found in recommendations issued by the International Commission on Radiological Protection (ICRP), which are the basis for most of the international and national basic safety standards. In relation to releases of
radioactive materials to the environment, the following radiation protection conditions apply:

(a) The total dose from all sources to individual members of the public — excluding natural background and medical exposure to patients — should not exceed the dose limits recommended by the ICRP [6,7]. Adherence to the dose limits, or any more restrictive limits originating in national regulations, maintains the individual risks within acceptable bounds.

(b) The total radiation detriment from any practice or operation should be justifiable in relation to the benefit that would not have been obtained otherwise from that practice or operation. As the distribution of benefit and detriment over the population is not the same, the benefit can be used to justify the detriment only if the total detriment to individuals is sufficiently low. This condition is ensured if all doses to individuals are below the dose limits recommended by the ICRP.

(c) All radiation doses from justifiable exposures should be kept as far below the dose limits as is reasonably achievable, taking into account social and economical considerations.

I–6. Condition (a) implies the assessment of the total exposure of members of a given population; conditions (b) and (c), on the other hand, imply an evaluation of all the exposures of future generations and of all the components of the world population which are related to a given source (see Chapter III).

I–7. In addition to the radiation protection conditions mentioned above, it is essential to take account of future radiation sources when limiting the discharges of present practices. This can be conveniently done by the assessment of the dose commitment per unit of practice.
(e.g. per MW(e) · a). As will be discussed later, this concept allows the prospective control of individual doses from routine operation of present and future multiple sources.

DOSE LIMITS

I—8. The dose limits given by the ICRP are expressed in dose equivalents for which the unit is the rem. These dose limits relate to individuals. They are intended for conditions where the source of exposure is subject to control, and, therefore, do not apply to doses from accidental releases. Also, the dose limits are intended to limit the doses received by individuals from all sources excluding doses from natural radiation sources and doses to patients from medical diagnostic or therapeutic applications. The exclusion of these two latter exposures is logical because the implied assumption of a direct proportionality relationship in the low dose range between risk and accumulated dose also implies that any dose increment carries a risk which is independent of previous doses.

I—9. The risk from medical exposure can therefore be assessed in relation to the direct benefit to the patients. The risk from natural radiation is assumed not to affect the additional risk from man-made sources of radiation. The latter risk may therefore be assessed separately, in relation to the expected benefit of such sources. Natural radiation doses may, however, be useful for reference purposes to place in perspective the significance of additional low doses of radiation. Natural radiation levels vary quite substantially from place to place and even locally. The extent of this variation is of practical interest since it may influence attitudes toward incremental exposures of individuals and population groups to man-made sources.

I—10. The dose limits recommended by the ICRP for individual members of the public are given in terms of annual limits and are 1/10 of the maximum permissible doses for persons engaged in radiation work.
I–11. The compliance with the dose limitation system for members of the public is determined not by monitoring all individuals but by assessments by means of sampling the environment and by verifying assumptions related to the exposure model linking the discharges and the doses. The actual doses received by individuals will vary, depending on several specific factors, and it is difficult to determine the maximum dose that might be received by a specific individual. In practice it is possible to make sure that this variability does not cause an under-estimate of the risk by the selection of appropriate critical groups within the population, provided the critical group is reasonably homogeneous with respect to the parameters that affect the dose received. Such a group should be representative of those individuals in the population expected to receive the highest dose, and the ICRP states that it is reasonable to apply the appropriate dose limits to the mean dose of this group.

I–12. ICRP Publication 26 [7] does not propose dose limits for populations. The genetic dose should represent the result of the sum of various minimum contributions, each justified by the benefits that otherwise would not be received. ICRP Publication 26 (Ref. [7], para. 129) further states that it is very improbable that responsible authorities would permit the average dose equivalent in a population to reach values that are more than small fractions of the former genetic dose level of 5 rem in 30 years. The genetic dose to a population is the dose which, if it were received by each person from conception to the mean age of childbearing, would result in the same genetic burden to the whole population as do the actual doses received by the individuals. The genetic dose can be assessed as the annual genetically significant dose, as defined by UNSCEAR [2–4], multiplied by the mean age of childbearing which may be taken to be 30 years.

I–13. The dose limits apply to controllable situations. They imply agreement on a maximum acceptable individual risk and are not related to any assumed non-linearity or threshold in the dose-risk relationship.
I—14. The dose limits are not applicable in non-controllable situations, e.g. an existing high environmental contamination resulting from an accident. In such cases some remedial action might be considered, such as discarding contaminated food. For such actions little guidance will be expected from comparisons with the dose limits. Instead, action levels may be derived from risk-benefit considerations of contemplated actions.

I—15. Action levels (e.g. of projected doses) can only rarely be determined in advance, unless the type of action and its consequences are known. Under some circumstances non-action levels may be specified in advance, below which possible actions can generally be said to be unjustified.

COLLECTIVE DOSE AND DETRIMENT

I—16. Some radiation protection measures require the assessment of collective dose in a given organ or in the whole body. The collective dose, \( S \), in a population, consisting of \( N \) individuals, is defined as

\[
S = \bar{H}N
\]

where \( \bar{H} \) is the per caput dose equivalent received by the individuals. Sometimes \( \bar{D} \), the per caput absorbed dose, is used instead of \( \bar{H} \). It is often necessary or convenient to assess the collective dose for groups in the population. A group \( j \), consisting of \( N_j \) individuals, receiving a per caput dose \( \bar{H}_j \), gets a collective dose

\[
S_j = \bar{H}_j N_j
\]

The total collective dose in the population is thus

\[
S = \sum_j S_j = \sum_j \bar{H}_j N_j
\]
It is recognized that in practice, in carrying out the summation of the collective doses $S_j$ of the various groups $j$, there may exist wide uncertainties which have to be considered.

I—17. The unit of collective dose equivalent or collective absorbed dose is the product of a dose unit (rem or rad) and a number unit of individuals (man); the resulting units are man-rem or man rad, respectively. The collective dose can be used to assess the mathematical expectation of the number of deleterious effects for a given organ in a given population, under the assumption of direct proportionality between dose and effect (see para.1—3).

I—18. The *detriment* in a population, as defined by the ICRP, is the mathematical expectation of harm incurred from a radiation dose, taking into account not only the probabilities of each type of deleterious effects but the severity of the effects as well. Thus, if $p_{ij}$ is the probability of suffering an effect $i$, the severity of which is expressed by a weighting factor $g_{ij}$, then the detriment, $G_j$, in a population group $j$, composed of $N_j$ persons, is

$$G_j = N_j \sum_i p_{ij} g_{ij}$$

For exposures resulting in small dose increments to doses of similar order of magnitude, for example small dose increments above the natural background, it may be assumed as a first approximation that

---

2 Although there is no universal agreement on severity weighting factors, one possible approach would be to use the probability of death from a given effect. Other approaches might employ relative life-span shortening as the measure of severity [8].
the increment of risk is proportional to the increment of dose. Under this assumption, each $p_{ij}$ will be directly proportional to the average dose in the range of interest

$$p_{ij} = r_{ij} \bar{H}_j$$

where $r_{ij}$ is a risk factor, the value of which is not known with certainty [1,5,6,9]. Assuming further that the severity of each effect is independent of its frequency, the detriment $G_j$ to an organ or to the whole body subsequent to uniform exposure to penetrating radiation can be expressed as

$$G_j = S_j \sum_i r_{ij} g_{ij}$$

where the sum is a constant independent of the collective dose $S_j$. The values of $r_{ij}$ and $g_{ij}$ may in some instances depend on such properties as age structure in the sub-population, but it is often possible to assume a common set of values $r_i, g_i$ for all sub-populations of interest. In that case the detriment in the total population is

$$G = \sum_j G_j = S \sum_i r_i g_i$$

As the collective dose applies to specific organs, the total detriment from a given source may consist of a sum of detriments caused by irradiation of a number of organs. Furthermore, if more than one radiation source exists which can cause detrimental effects in a population, then these sources have to be considered in the assessment of the overall detriment in the population.
GENERAL CONCEPTS

I–19. With the assumptions indicated above, the detriment in the population concerned is directly proportional to the collective dose in an organ. For comparison with benefits when assessing the justification of a source, or with costs involved in the reduction of a given radiation level (Chapter IV), it is convenient to assign a monetary value to the collective dose unit. This could be attempted using different approaches, such as to give a value to the sum

\[ \sum_{i} r_{ig_{i}} \]

by actually assessing the impact on society by the deleterious effects of concern, or by observation of the values society actually is willing to pay to reduce collective doses in given practices. Several assessments of the cost equivalent of a man rem have been published in the literature [10–17].

I–20. Values ranging from US $10 to about US $1000 have been deduced from reported information based on assessments of risk and 'cost of life' [3,4,9–15], assuming a death probability of 10^{-4} per rem. The BEIR report of the Advisory Committee of the US National Academy of Sciences [9] gives as an example an estimate for the direct medical costs of genetically related ill-health only between US $12 and US $120. Studies of the values society is willing to pay to reduce the total health impact of collective doses give somewhat higher values for a man-rem, up to US $1000 [10].

I–21. It should be noted that all these values refer to whole-body irradiation. For exposures of specific organs, e.g. the thyroid, the detriment corresponding to a collective dose unit would be lower and, correspondingly, the cost equivalent of the man-rem would also be lower than the values quoted in the preceding paragraph.
DOSE COMMITMENT AND COLLECTIVE DOSE COMMITMENT

I–22. The collective dose commitment $S^c$ [8], resulting from a given practice or operation, is defined as the infinite time integral of the per caput dose rate caused by that decision, practice or operation in a given population, multiplied by the instantaneous size of that population. Thus,

$$S^c_H = \int_0^\infty \bar{H}(t) N(t) \, dt \tag{1}$$

where $\bar{H}(t)$ is the per caput dose rate, and $N(t)$ is the instantaneous population size. The collective absorbed dose commitment $S^c_D$ is defined in complete analogy. Thus,

$$S^c_D = \int_0^\infty \bar{D}(t) N(t) \, dt \tag{1a}$$

where $\bar{D}(t)$ is the per caput absorbed dose rate. If $N(t)$ is constant with time, i.e. $N(t) = N_0$, then

$$S^c = N_0 \int_0^\infty \bar{H}(t) \, dt$$

where the integral is the dose commitment. UNSCEAR [18,19] uses the per caput absorbed dose rate $\bar{D}$ and therefore the absorbed dose commitment

$$D^c = \int_0^\infty \bar{D}(t) \, dt$$
GENERAL CONCEPTS

I—23. The population over which the dose rate is averaged may not consist of the same individuals over the integration period; it may, in fact, comprise many generations.

I—24. Reliable estimates of collective dose commitments are difficult to make in cases where releases may result in very long-lived radionuclides contaminating the environment.

COLLECTIVE DOSE COMMITMENTS FROM FUTURE SOURCES

I—25. In Chapter IV, the process of differential cost-benefit analysis is discussed as a general means to rationally implement the requirement 'to keep radiation exposure as low as is reasonably achievable ....'. For the differential cost-benefit analysis process to be made, the collective dose commitment has to be assessed. The assessment of $S^{c}$ should take into consideration existing sources, sources in the planning stage, and foreseeable future sources in order to optimize control of releases to the environment on a site-specific basis, as well as to allow the examination of potential future doses relative to the dose limits or more restrictive national authorized limits.

I—26. If the sites and characteristics of planned sources are known, the differential cost-benefit analysis should take account of these sources. However, the sources foreseeable in the longer term, depending on future technological and economic development, have generally not been the subject of a decision with respect to their siting. The differential cost-benefit analysis can in this case lead to an optimization for siting purposes based on the optimization of releases in an appropriate sector of the environment.

I—27. If the rate of total nuclear energy production planned in a given country is $Z$, and if the collective dose commitment per
unit of practice is $S^c_1$, then the collective dose rate at steady state, $\dot{S}_\infty$, is (see Appendix 1)

$$\dot{S}_\infty = Z S^c_1$$

(2)

If only the $N_j$ individuals constituting that country’s population were exposed, the per caput dose rate at steady state, $\dot{H}_j$ would be

$$\dot{H}_j = \frac{\dot{S}_\infty}{N_j} = \frac{Z S^c_1}{N_j}$$

(3)

This concept can be extended to the global collective dose commitment by replacing the national parameters in Eq.(3) by the respective estimates of the future world nuclear power generation and the projected world population.

I–28. The use of the collective dose commitment for the whole world population as a means of controlling the future per caput dose rate from all sources is not in itself based on any biological assumptions. It is purely the mathematical consequence of the fact that the per caput dose rate, $\dot{H}$, at the time when it is maximum, will be

$$\dot{H} = \frac{1}{N} \sum_k (S^c_1)_k Z_k$$

where $N$ is the world population, $(S^c_1)_k$ is the collective dose commitment per unit of practice of source $k$, and $Z_k$ is the rate of practice of source $k$.

I–29. For exposures delivered over a very long time it would not be realistic to assume a continued practice for such long times as
required for the per caput dose rate to approach the steady state. In these cases it would be unnecessarily restrictive to limit releases on the basis of the dose commitment per unit of practice. As shown in Appendix 1, the limitation can be achieved by the use of the integral of the per caput dose rate due to a unit of practice over a time equal to the estimated duration of the continued practice. For controlling the future per caput annual doses in the world population from the use of nuclear fission power, the relevant time would be the length of that practice. Forecasts of that length have been published [19] and are of the order of several hundreds of years. The limitation of releases would be affected only to a small degree by the actual selection of the integration time, and a value of 500 years has been used in some assessments [19].

I–30. Similarly, for the purpose of controlling the future per caput annual dose in a regional population from installations in the region, the integration may be carried out over the operational time of all installations planned for the region.

I–31. A more detailed discussion of the use of collective dose and collective dose commitment for sources in the optimization implied in the concept ‘as low as reasonably achievable’ is presented in Chapter IV of this report.

MODELS RELATING RADIATION DISCHARGES, ENVIRONMENTAL LEVELS AND DOSES

I–32. The movement of radionuclides from the source can be described mathematically by environmental models. Such models are of varying complexity and often compartment models are used in which the rates of transfer of radioactivity between compartments are specified by constants or by time functions. This modelling is similar to that used in many engineering activities and is called systems analysis. The
use of compartment models normally implies considerable simplifications of the real transfer processes. This, however, does not impair their usefulness in the present context provided the functions specifying the rates of transfer are properly chosen.

I—33. By using systems analysis it is possible to predict levels in the environment and, given sufficient information about population characteristics, dose rates in members of the population as a function of time, for single, protracted, and continuous releases of radioactive materials.

I—34. In most practical cases, for the purpose of radiation protection, it is sufficient to assess the dose commitment resulting from a given release. Exceptions are the collective dose commitments associated with long-lived radionuclides. In the case of shorter lived radionuclides, the time functions describing dose rates and the concentration in different compartments of the environment need not be evaluated because the time-integral values of these variables provide the information required.

I—35. If the movement of radionuclides in the environment is described by a non-feedback transfer model, a knowledge of the transfer factors as defined by UNSCEAR [18] will be sufficient to predict the time-integral values mentioned above. In general, these transfer factors are defined as quotients between time integrals of quantities linearly related to dose, in different compartments. In the present context the transfer factor $f_{uv}$ relating compartments $u$ and $v$ is defined by

$$f_{uv} = \frac{\int_0^\infty C_v(t) \, dt}{\int_0^\infty C_u(t) \, dt}$$
where \( C_u(t), C_v(t) \) are the concentrations in the compartments \( u \) and \( v \) at time \( t \).

I—36. In case of continuous release at a constant rate, and provided that the environmental conditions governing the transfer processes remain relatively constant with time (or that they can be adequately characterized by average parameters), it can be shown that the same transfer factors cover the steady state condition.

\[
f_{uv} = \frac{C_v}{C_u}
\]

I—37. This is usually the situation involving continuous routine releases, where for relatively short-lived radionuclides constant relationships can be assumed between the rate of discharge and the concentration of the radionuclides in the environment since steady state may be reached rapidly. The annual doses received in this case are equal to the dose commitments from one year of releases (see Appendix 1).

I—38. Assessing the doses from these chronic discharges or the dose commitment from a given practice can in principle be done by using the time-independent model outlined above. This is usually known as the \textit{equilibrium model} or, because the transfer factors in this case are ratios of concentrations (i.e. concentration factors), \textit{the concentration factor model}.

I—39. Experience has shown that, when radioactive materials are introduced into the environment, a few nuclides and certain exposure pathways will be much more important than others and will be responsible for most of the dose received by individual members of the public. These nuclides and pathways are designated 'critical'.

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CHAPTER I

DERIVED LIMITS

I—40. The use of environmental models allows the establishment of relationships between discharges, environmental levels and resulting doses, making it possible to relate releases of radioactive materials into the environment to radiation protection requirements, given as dose commitment limits.

I—41. The basic requirement that the individual dose limits are not exceeded (i.e. that the average dose in the critical group does not exceed the dose limits) is implemented by application of derived limits (DL). The DL for release into the environment is defined as the annual input of radioactivity of specified composition, which will result in a dose commitment in the critical group equal to the recommended annual dose limit.

I—42. Derived limits for environmental contamination are defined in an analogous way. Thus, the DL for environmental contamination is defined as the annual average contamination level which, under steady state conditions, gives an annual average dose to the critical group equal to the recommended annual dose limit.

DISCHARGE LIMITS AND OPERATIONAL LIMITS

I—43. In practice, release limits are usually set at levels which will only correspond to small fractions of the relevant environmental DL. In many cases it can be shown by differential cost-benefit analysis that it is reasonably achievable to keep the releases this low. In addition, however, allowance must be made for releases from other sources, including the foreseen development with time.

I—44. When setting actual release limits for a justified source, the following requirements have to be met:
(a) Dose limits for individual members of the public (i.e. the critical group) must be complied with. Therefore, the annual discharge must be smaller than the DL for release. Chapter II of this report gives the required relations between releases and doses in the critical group.

(b) Doses must be kept 'as low as reasonably achievable'. This implies an optimization of protection, and the value of the annual discharge that meets this requirement is obtained by differential cost-benefit analysis as described in Chapter IV. A necessary condition is that the discharge is at most equal to DL; usually it is much smaller, which implies that the dose in the critical group is correspondingly smaller than the dose limit.

(c) In establishing release limits, consideration must be given to the presence of other sources as well as to future installations. Two conditions will have to be considered:

1. In a local sector of the environment, the total of the 'optimized' annual releases from a given source must be small compared to the DL for annual discharge to allow for other sources.
2. The average dose resulting from a practice would have to be controlled. This can be done by setting a limit to the collective dose commitment per unit of practice ($S_p$), as is mentioned in para. I–28 and is presented in detail in Chapter IV.

I–45. The implementation of requirements (b) and (c) requires the calculation of collective dose commitments. Methods for assessing these are outlined in Chapter III of this report.

I–46. The 'optimized' discharge limit may be used by the authorities as the 'authorized operational limit'. In some instances the authorities may want to base the authorized limit on the application of a safety
factor to the derived level, due mainly to uncertainties in the adopted environmental model and to insufficient information to allow the optimization process.

REFERENCES TO CHAPTER I


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Chapter II

ASSESSMENT OF DOSE TO THE CRITICAL GROUP

AIMS

II—1. As seen in Chapter I, for the assessment of the health detriment of a certain release of radioactive material to the environment, as well as for the purpose of controlling present and future releases, it is essential to assess the collective dose and the collective dose commitment resulting from that release.

II—2. The collective dose equivalent is given by

\[ S = \sum_j S_j = \sum_j H_j N_j \]

where \( H_j \) is the per caput dose to individuals constituting the group \( j \), as indicated in para. I—16. Experience has shown that, when radioactive materials are introduced into the environment, a few radionuclides and certain exposure pathways will be much more important than others and will be responsible for most of the dose received by individuals in the group. These individuals, radionuclides and pathways are designated as 'critical'. Para. I—5 requires that \( H_j \) shall not exceed the appropriate ICRP individual dose limits.

II—3. The aim of this chapter is to enunciate the basic principles and methodology used in deriving the value for the rate of release of a radioactive effluent via critical pathway analysis which would deliver
a dose to the critical group equal to the ICRP dose limit\(^3\). This should not be taken to imply that such a release rate should be permitted; on the contrary, actual release rates authorized by national authorities will normally be much lower. The model is given here only for purposes of calculating the relationship between annual release rate and annual dose and is used as a means of determining whether the basic objective (para. I—5(a)) that doses to individual members of the public shall not exceed the dose limits recommended by the ICRP is met [1, 2].

II—4. The quantities calculated from the critical pathway model which follow are, therefore, the derived limits for effluent release rate. Further quantities which may be calculated are the levels of environmental contamination which would occur if releases were made at this limit; these are the derived limits for environmental contamination.

CRITICAL PATHWAY ANALYSIS [3–9]

II—5. The operation of installations handling radioactive materials will release some radioactivity to the environment. The composition of the effluents will vary as will the sector of the environment to which they are released: individual environments will have different physical, chemical or biological characteristics, and human utilization of the environment and the possible modes of human radiation exposure will also vary between environments. The situation is potentially very complex, but practical experience at a wide variety of operating sites shows that a comprehensive study of all possible pathways is not always required. An outline study of the problems will indicate which radionuclides in which potential exposure pathways are likely to be important — these are the critical pathways and critical radionuclides. In most situations, only a few radionuclides in a few pathways will emerge as

\(^3\) A more general approach to discharge limitation may be found in Appendix 2.
much more important than all others, from the standpoint of evaluating potential exposures and establishing discharge limits, and the detailed evaluation of these critical radionuclides and pathways then becomes the essential pre-operational task. The correct assessment and control of these pathways will set the maximum rate of release of radioactive materials and ensure an adequate control of all other pathways. Normally it is possible to find a group in the population potentially at risk, which clearly is in a position to receive a higher exposure from a given source than all other parts of the population — this is the critical group in ICRP terms, and its identification and detailed examination in terms of pathways and transfer mechanisms leading to its exposure is a primary aim of critical pathway analysis.

II—6. The critical pathway assessment has as its basis an evaluation of the network of all potential exposure pathways. This evaluation is made by using transfer models for the individual pathways, and it is normally possible to identify a small number of potential critical pathways, radionuclides and population groups by application of quite crude models. The possible critical pathways are then analysed more closely using detailed, quantitative models. The aim is to develop a relationship between unit rate of introduction of radioactive material and the resultant radiation dose to potential critical groups, and thus to establish from the ICRP dose limits for members of the public a derived limit, i.e. the annual input of radioactivity of specified composition which will result in a dose commitment in the critical group equal to the recommended annual dose limit (see para. I—41).

II—7. Such an assessment is not intended to provide an accurately computed figure for the maximum permissible discharge rate; it is only an approximation required for the purpose of initial planning. The early years of discharge may provide the necessary opportunity to establish more precise figures. Neither will all situations require an exhaustive application of a full investigation, though, in principle, it will always
be necessary to consider the various stages to some degree. Furthermore, during the operational lifetime of the source, a continuing review of release and environmental monitoring data is necessary for the verification of the pathway model used.

II—8. The safety evaluation of a nuclear installation includes a survey of the local environment to establish those uses which will lead to radiation exposure, e.g. food consumption, use of water as drinking water, or human presence near contaminated soil or beach sand. These data are used together with estimates of radionuclide concentrations in the recipient medium, related to unit rates of introduction of the radioactive material, to assess the resulting doses which then could be compared with the ICRP dose limits to arrive at the maximum permissible rates of introduction.

INFORMATION NECESSARY FOR THE MODEL

II—9. Dose assessment includes consideration of at least the source term; the transport, dilution and cycling of radioactive materials in environmental media; the characteristics of the recipient including the human use of the environment; and the calculation of dose and comparison of dose with appropriate limits.

EFFLUENT COMPOSITION

II—10. Here, as thorough as possible a knowledge is required of radionuclide composition and of chemical or physical state, in order to predict the likely behaviour of the effluent and its individual radionuclides as they are introduced into the environment. Data on gaseous, liquid and solid components, density, particle size, temperature, mode of discharge etc., are valuable, as may be information on other non-radioactive matter in the effluent which may determine or modify the behaviour of the radioactive constituents after their introduction to
the environment. In many situations only estimates will be available, and refinements, if necessary, will only become possible in the operational phase.

DILUTION AND DISPERSION IN THE RECEIVING MEDIUM [9–11]

II–11. Radionuclides introduced into the environment in gaseous, liquid, particulate or gross solid form are subject, on varying time scales, to some degree of dispersion and dilution. The degree of dispersion depends not only on their physical state in relation to that of the receiving medium, but also on distance from the source and the way of introduction. This, in turn, will depend to some extent on temperature and density differences between the effluent and the recipient medium, at what depth in water, or height in the atmosphere it is introduced, on its rate of introduction relative to factors such as river flow, ground water movement and turnover, tidal current, wind speed and direction, atmospheric turbulence etc. Two further factors which must be taken into account are the fractionation which occurs between different components of the receiving environment (e.g. water and sediment), and ageing processes which will modify the extent to which a radionuclide is available for transfer through subsequent stages of a pathway. All these factors need to be considered in order to determine dilution and dispersion.

II–12. The rate at which subsequent dilution will proceed will be determined in the case of liquid and gaseous effluents by transport processes in the medium, and the effects of these processes themselves are dependent on the local hydrographic and atmospheric conditions. Solid material in these wastes may, if in finely divided particulate form, be subjected to some initial dilution and dispersion before sedimentation or deposition, and these processes and their interactions will need to be taken into account. Solid wastes may eventually dissolve or break up and thus become subject to some degree of dispersion, and this possibility will also need to be assessed.
CHAPTER II

II—13. The major aspects of these problems will not be developed in detail here. Suffice it to note that several models providing adequate quantitative descriptions of these processes are available for application to aquatic and atmospheric environments [10—17]. In general, very detailed hydrographic and atmospheric studies of individual sites involving the use of tracer techniques will not be necessary. Calculations using simple conceptual models such as, in the case of sea water, homogeneous distribution in the available volume, or Gaussian plume models for atmospheric dispersion coupled with appropriate loss terms such as deposition velocities, wash-out coefficients, radioactive decay or data on run-off, or the location, movement and turnover of ground water, will be adequate.

II—14. Basically, all processes, other than radioactive decay, which lead to depletion of the concentration in the primary receiving medium, result in transfer to other compartments of the environment. Transfer to and reconcentration in or on biological or physical materials as well as resuspension processes in an equilibrium, or steady state situation have to be considered. It is adequate to use concentration factors at equilibrium for the evaluation of such transfers.

TRANSFER TO CRITICAL ENVIRONMENTAL MATERIALS

II—15. In an aquatic environment, predicted concentrations in the receiving water mass are converted by use of appropriate concentration factors to concentrations in critical environmental materials. These factors are known for a wide range of materials and radionuclides from actual operational situations, and many more have been determined experimentally or by stable nuclide analysis of water and other matrices. Sufficient data of adequate quality for a substantial number of situations exist on which to base many calculations of the requisite accuracy for hazard evaluations [18—26]. A somewhat different approach to the use of concentration factors is required in the atmospheric case for
deposited materials where, after calculation of concentrations in air, estimates must be made, for example in the case of food contamination, of the relationship between concentration in ground-level air and radioactivity levels in vegetation and grazing animals [9, 27, 28]. The decrease of radioactivity in the environment by radioactive decay or by environmental removal processes such as weathering should be taken into account.

ENVIRONMENTAL HABITS SURVEY [7, 29]

II–16. Data are required on the uses of the local environment which may lead to human radiation exposure, and these are obtained after a preliminary survey of the area to ascertain potential exposure pathways. The preliminary survey usually indicates a few pathways worthy of more detailed evaluation — consumption of particular foodstuffs, occupancy of areas subject to contamination giving rise to external exposure, use of water as a human drinking water supply or for irrigation or livestock drinking purposes, handling of contaminated fishing gear etc. Each of these pathways will then need to be evaluated in order to determine the distribution of food consumption rates, of occupancy times in contaminated areas, or of time spent handling contaminated materials etc. As a result of these assessments it will become possible to identify those members of segments of the population likely to receive the greatest radiation exposure. In most cases these will be small groups and it will be possible to identify the people potentially exposed, and thus, in principle, to set limits to the rate of introduction of radioactive material sufficient to protect all.

II–17. In some instances, however, the population at risk will be large, as in the case of contamination of a major drinking water supply and dispersion of $^{85}$Kr throughout the world’s atmosphere, or where the summation of the effects of many small, well-dispersed point sources leads to the exposure of a large segment of the population. Experience
to date indicates that even where significant numbers are exposed, it is usually the somatic risk posed to a few individuals which presents the limiting exposure situation.

II—18. In those cases where the population at risk is large or where the critical group is not readily identifiable, it will often only be possible to establish the habits of a representative sample of the population and to identify a group within this sample whose habits, with respect to those factors which determine the dose received, lead to the highest doses in comparison to the appropriate dose limit. Limits for discharge are then calculated so as to limit exposure such that the average dose to this group, the critical group in ICRP terms [3], does not exceed the dose limit for members of the public.

CALCULATION OF DOSE

II—19. In the case of external exposure pathways, the dose is obtained by applying the appropriate dose-rate conversion factors and taking into account shielding effects, annual rate of occupancy and other modifying factors. In the case of internal exposure, the relation between intake and dose must be established by means of metabolic models. This has been done by the ICRP using the standard man concept [2, 30, 31]. It should be noted that wide regional variations in the relevant metabolic and physical parameters exist which may necessitate modifications of the parameter values when applied to the local situation [32].

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4 See ICRP Publication 23 (1975) — Report of the Task Group on Reference Man, where more comprehensive information is available with respect to reference man, woman and child.
IDENTIFICATION OF CRITICAL GROUP [3, 8]

II-20. The actual identification of a critical group presents some difficulties, as can be seen in the case of a marine discharge, where the critical material is a foodstuff [31, 33, 34]. ICRP only gives general guidance on the matter [3]. Where the primary variable leading to radiation exposure can be confidently identified, e.g. food consumption rate, and provided a suitable distribution of this variable in the exposed population can be found, various statistical techniques are available which may be used to assist definition of the critical group. However, the use of these techniques still needs to be tempered with common sense. The critical group should be identified in such a way that it is representative of the more highly exposed individuals in the population and is as homogeneous as practicable with respect to radiation dose, that is, with respect to the following factors which affect the dose in the specific case considered.

(a) Location, physiologic and metabolic characteristics and age distributions of the potentially exposed group;
(b) Dietary habits, e.g. foodstuffs and amounts consumed;
(c) Working habits, e.g. commercial fishing, dredging and earthwork maintenance;
(d) Domestic habits, e.g. time spent indoors;
(e) Type of dwelling, e.g. shielding characteristics or ventilation;
(f) Recreational activities, e.g. sport, fishing or swimming.

In any case identification of a group on the basis of the distribution of any one variable such as consumption rate or occupancy factor may not be the final step in the process since the group may require further sub-division on the basis of age, sex, or individuals subject to additional exposure via other routes. Such considerations may require the setting of more stringent limits than would be dictated in relation to a single pathway.
CALCULATION OF DERIVED LIMITS

II—21. Derived Limits (DL) may be calculated in terms of either discharge rates (sometimes referred to as environmental capacities) or levels of environmental contamination. In the former case, the full critical pathway model is used, whereas in the latter, only the stages of the pathway model are used that involve exposure of man from the critical material. The discharge rates normally vary with time and the characteristics of many environmental pathways show pronounced seasonal variations; it is therefore necessary to select a long enough time — normally one year is used — as the averaging period for estimating DL values.

DERIVED LIMITS FOR ANNUAL DISCHARGE

II—22. Derived limits may be calculated by either the concentration factor method or the more inclusive systems analysis method. However, to estimate the DL for the critical pathway, it is often sufficient to use the concentration factor method for the calculation. In order to estimate derived limits for annual discharge it is necessary to know the relationship between discharge and the dose commitment for the critical group. The information necessary for this is obtained by critical pathway analysis as discussed in paragraphs II—5 to II—18.

II—23. The end result of a critical pathway analysis can be summarized by a set of numbers $f_{jkl}$, relating the dose commitment from nuclide 1 in population group j and the unit discharge from source k. A release $R_{kl}$ from source k thus gives a dose commitment $H_{jkl}^c$ in population group j

$$H_{jkl}^c = f_{jkl} R_{kl}$$
In the simplest case, only one source $k$ and one critical nuclide $l$ has to be considered, and the critical group $j'$ is the one corresponding to the highest of the $f_{jkl}$ values. The DL is then given by one release value $R_{k1}^*$ which is related to ADL, the appropriate ICRP recommended annual dose limit, by

$$\text{ADL} = f_{j'kl} \cdot R_{k1}^*$$

II—24. If there are a number of sources $k$, but still only one critical nuclide $l$, it is in general necessary to prescribe a set of release values such that

$$\text{ADL} = \sum_k f_{j'kl} \cdot R_{k1}^*$$

When the releases from different sources are interdependent, this equation defines a set of $R_{k1}^*$ values. If the releases can be varied independently, the $R_{k1}^*$ values are not uniquely determined, but can to a certain extent be adjusted in order to optimize the total operation. It should be noted that the critical group may change when the proportions between releases are changed, thus necessitating a re-calculation of the $R_{k1}^*$ values using a new set of $f_{j'kl}$ values.

II—25. In the case when a number of nuclides $l$ contribute significantly to the exposure of the critical group $j'$, and these nuclides all relate to the same critical organ, the $R_{k1}^*$ values must satisfy the condition

$$\text{ADL} = \sum_k \sum_l f_{j'kl} \cdot R_{k1}^*$$

which, as in the preceding case, does not uniquely determine release values, unless the releases are interdependent.
II—26. When there is a significant exposure of more than one organ of the individuals in the critical group, this should be taken into account according to the procedure given in Refs [1, 35]. With this modification, the release values have to satisfy the following condition for all organs, m,

$$ADL_m \geq \sum_k \sum_l f_{jklm}^* R_{kl}^*$$

II—27. The recently published ICRP recommendations [35] suggest that the dose limitation for stochastic effects\(^5\) is based on the principle that the risk should be equal irrespective of whether the whole body is uniformly irradiated or is subject to non-uniform irradiation. This condition is met if

$$H_{WB,L} = \sum_m w_m H_m$$

where $H_{WB,L}$ is the recommended annual dose equivalent limit for uniform irradiation of the body, namely 5 rem, $w_m$ is a weighting factor given in ICRP Publication 26 [35] representing the proportion of the stochastic risk resulting from the irradiation of tissue or organ, m, to the total risk, when the whole body is irradiated uniformly. $H_m$ is the dose equivalent in tissue or organ, m. Then the release values $R_{kl}^*$ satisfying the dose limit conditions would, with a margin of safety, be given by

$$\sum_k \sum_l \sum_m w_m f_{j"}^{(klm)klm} R_{kl}^* = ADL$$

\(^5\) To prevent non-stochastic effects, ICRP Publication 26 suggests the application of a dose equivalent limit of 50 rem per year to all tissues except the lens, for which a limit of 30 rem per year is suggested.
where $\text{j}''(\text{klm})$ indicates the population group receiving the highest dose in organ $m$ due to nuclide $1$ and source $k$. $R_{kk}^*$ will not uniquely determine any one release limit value but is part of any set of release values which, combined, will constitute a release at the limit. The fact that $\text{j}''(\text{klm})$ implies addition of weighted organ doses in different critical groups brings in a margin of safety, but the selection of the highest organ doses irrespective of critical group greatly simplifies the calculation.

II—28. With a very large number of sources distributed all over the world, the global contamination could conceivably become a problem and it would be prudent to make the above assessments also for the whole world population as the critical group.

II—29. Critical pathway analysis also provides a framework for design of a monitoring system for estimation of radiation dose received by the groups in the population. In addition, if contamination becomes measurable following the commencement of operation, environmental monitoring may provide a means of checking the validity of the overall model and enable the relationship between discharge and dose to the critical group to be reassessed with greater accuracy than is possible before operation has begun. In these circumstances the need to assume an effluent composition is avoided as is also the use of aquatic or atmospheric dispersion models and models descriptive of the environmental transfer process.

DERIVED LIMITS FOR ENVIRONMENTAL CONTAMINATION

II—30. Sometimes it is of interest to calculate derived limits for environmental contamination. They are the contamination levels equivalent to the ICRP recommended dose limits. Their main application is as a comparative index for use in judging the relative importance of contamination levels.
II—31. Derived limits for environmental contamination are calculated in the same way as for discharges. The average activity concentration of nuclide 1 in an environmental compartment v, \( C_{lv} \), results in an average annual dose equivalent \( H_{jlv} \) in population group j.

\[
H_{jlv} = f_{jlv} C_{lv}
\]

The numbers \( f_{jlv} \) can then be used to calculate values of environmental activity concentration, corresponding to the ICRP dose limits, in the same way as the release values are calculated. When only one nuclide 1 and one environmental compartment v is considered, ADL thus corresponds to one value of the contamination level, \( C^*_v \), i.e.

\[
ADL = f_{jlv} C^*_v
\]

APPLICATION OF DERIVED LIMITS [1, 3, 36]

II—32. The most that critical pathway analysis can indicate is the annual average discharge of the effluent that would relate to exposure of the critical group at a specific annual dose such as the ICRP dose limit. However, in deriving this relationship it provides a tool by use of which national authorities can come to a decision as to the rate of discharge which can be authorized and which will ensure that a particular limitation on annual dose is met.

II—33. Application of the derived limit for the annual average discharge of the effluent will therefore depend on the way in which decisions on annual dose limitation are arrived at. Ideally, such decisions should be made only after careful consideration of the justification and optimization procedures involving cost-benefit analysis described in Chapter IV for which methods of assessing collective dose commitment as outlined in Chapter III are also needed.
REFERENCES TO CHAPTER II AND APPENDIX 2


CHAPTER II


CHAPTER II


[42] KAYE, S.F., NELSON, D.J., Analysis of specific activity concept as related to environmental concentration of radionuclides, Nucl. Saf. 9 (1968) 53.


Chapter III

ASSESSMENT OF COLLECTIVE DOSE COMMITMENTS [1]

AIMS

III—1. The total collective dose commitment from a given source or sources may be determined for the following reasons:
   (a) The collective dose commitment resulting from a source is used in cost-benefit analysis and differential cost-benefit analysis for the purpose of assessing the justification of the source and for the optimization of protection;
   (b) The collective dose commitment from all sources including all foreseen future sources is used for the purpose of evaluating the future average dose to the world population.

III—2. The collective dose commitment, $S^c$, from an event, practice or decision is obtained as the infinite time-integral of the collective dose rate, $\dot{S}(t)$, caused by this event, practice or decision [2]

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

(4)

The collective dose rate, $\dot{S}(t)$, is defined as the weighted product of dose rate and number of individuals of the population

$$\dot{S}(t) = \int_0^{\infty} H \cdot N_H(\hat{H}, t) \, d\hat{H}$$

(5)
where $N_H(\dot{H}, t)$ is the population spectrum in dose rate, and $N_H(\dot{H}, t) d\dot{H}$ being the number of individuals receiving a dose rate in a specified organ or tissue in the range $\dot{H}$ to $\dot{H} + d\dot{H}$ at time $t$. It can be readily shown that the collective dose rate can also be assessed by the expression

$$\hat{S}(t) = \sum_j \bar{H}_j N_j(t)$$

where $\bar{H}_j$ is the per caput dose rate in population group $j$, and $N_j(t)$ is the size of that group as a function of time, $t$. The dose rate incurred is due to a specified decision or practice or a number of such specified decisions or practices.

III–3. In this chapter methods for assessing the collective dose rate, $\hat{S}$, are outlined. With knowledge of $\hat{S}$, the collective dose commitment, $S^c$, can be calculated according to Eq.(4).

III–4. When information on individual or per caput dose is not available, it may still be possible to estimate the collective dose commitment by indirect methods.

III–5. The individual dose (or dose commitment in the case of materials with long effective half-lives) from internal irradiation is in general directly proportional to the intake of radioactive material. There is individual variability and in some cases a pronounced variation with age of the quotient between dose and intake, however, it is often possible to find a population average value of this quotient that is valid for all reasonable distributions of intake within the population. The collective dose commitment can then be calculated by

$$S^c = f_d Q$$
where $Q$ is the total amount of radioactive material reaching the population and $f_d$ is a collective dose factor (expressed for example in man $\cdot$ rem/Ci). The factor $f_d$ can in general be the product of several constants, each representing one transfer step in the process linking the source and man. In the case of dietary contamination, the collective dose commitment is proportional to the collective intake of radioactive material, which in turn can be assessed by summation of the products of concentrations and the quantities of food consumed, assuming as a first approximation that all food produced is consumed.

III-6. A similar approach can sometimes be used for estimating collective dose commitment from external irradiation, e.g. when the irradiation is due to ground deposition of radioactive material. Thus the collective dose commitment in this case is directly proportional to population density and total activity deposited.

ASSESSMENT OF COLLECTIVE DOSE RATE TO THE WORLD POPULATION

III-7. The total collective dose rate to the world population from a given installation discharging radioactive material into the environment may be assessed by calculating the contributions from four components, namely the occupationally exposed population group, the local population, the intermediate population, and the rest of the world population.

III-8. The assessment of the collective dose rate component of the occupationally exposed individuals presents no great practical difficulty, as usually the number of individuals exposed and the individual annual doses are known. The second contribution is the product of the assessed per caput dose rate in the local group and the size of the group. The principles of the methods of deriving the dose in the local groups can be applied when assessing the per caput dose.
CHAPTER III

rate. Different environmental models are required for the assessment of contributions from the other components. The global component is usually assessed assuming uniform mixing in the relevant portion of the biosphere. For some nuclides this is a fairly adequate method, but in other cases more complicated models have to be used. The most difficult assessment is that of the intermediate component, but some models have been presented in the literature; for the atmospheric case see Refs-[3—7].

WEIGHTING PROCEDURES

III—9. For some types of exposures, a substantial fraction of the collective dose commitment may relate to exposures of individuals who, because of child expectancy or age, cannot manifest the effect which the dose received might produce. For example, if the persons exposed are beyond child-bearing age, genetic effects cannot become manifest; if the life expectancy is less than the latent period, carcinogenic effects may not become manifest. In order to make the result relevant for assessment of detriment, allowance must be made for these ineffective contributions by the application of weighting procedures (such as, for example, calculations of the genetically significant dose in the UNSCEAR reports [8]).

REFERENCES TO CHAPTER III


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ASSESSMENT OF COLLECTIVE DOSE COMMITMENTS


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Chapter IV

APPLICATION OF OPTIMIZATION TECHNIQUES TO THE DETERMINATION OF DISCHARGE LIMITS

INTRODUCTION

IV—1. The radiation protection of the public is based on compliance with the dose limitation system recommended by the ICRP (Publications 26 and 22). In addition to the quantitative dose limits, however, there are two requirements, derived from the assumption that any exposure may involve some degree of risk, which have to be fulfilled. These two requirements are:

(a) as any exposure may involve some degree of risk, the risk should be balanced by benefits which justify the exposure;
(b) all doses should be kept 'as low as reasonably achievable', social and economic considerations being taken into account.

The first requirement implies justification of the exposure, whilst the second implies optimization of benefits and the costs of radiation protection.

IV—2. For the justification of the exposure it is necessary to demonstrate that the detriment resulting from one or more radiation sources associated with a nuclear programme is balanced by the benefits resulting from its operation. This requires the use of the techniques of cost-benefit analysis, where two terms are compared, the costs and the benefits.

(a) The costs include all capital and operating expenditures, plus direct and indirect costs including intangibles associated with the effects of radioactive releases on man and his environment.
(b) The benefits include the value of the product incorporating all direct and indirect benefits including intangibles to the population as a whole.

IV—3. In a conceptual analysis, the net benefit, $B$, to be expected from a decision or operation may be expressed by the following equation:

$$ B = V - (P + X + Y) $$

where $V$ is the added value from introducing the operation, $P$ is the production cost (excluding protection costs), $X$ is the cost of protection, and $Y$ is the cost of detriment.

IV—4. The justification of a decision or a practice that could result in radiation exposure is beyond the scope of this document. For the remainder of this discussion it will be assumed that the introduction of a practice will result in a net benefit to society. The problem is reduced under this assumption to maximizing this net benefit by determining the optimal level of radiation protection.

OPTIMIZATION OF RADIATION PROTECTION

IV—5. In order to determine whether a given level of radiation protection satisfies the objective of keeping doses as low as is reasonably achievable, it is necessary to consider the benefits to society from further reductions in the cost of the radiation detriment and the additional costs to society of achieving these reductions. The optimal level of protection is reached when the additional cost of achieving further reductions in the collective dose commitment outweighs the decreased cost to society of the detriments arising from this dose.

IV—6. For a given practice, both the cost of protection, $X$, and the cost of the radiation detriment, $Y$, can be expressed as functions
of collective dose commitment $S_A^c$. Given a level of protection, A, its total cost, $U_A$, is equal to the sum of protection cost, $X(S_A^c)$, and the cost of the detriment, $Y(S_A^c)$, and is, consequently, also a function of the collective dose commitment at this level of protection, i.e.

$$U(S_A^c) = X(S_A^c) + Y(S_A^c)$$

**IV—7.** The cost of the health detriment due to radiation, i.e. Y, will increase proportionally to the collective dose commitment as illustrated by curve Y in Fig.1. Correspondingly, a decrease in the collective dose commitment normally will require a higher expenditure for protection. This relationship, however, is not likely to be a linear function. Initial expenditures are likely to achieve a large reduction in the collective dose commitment, whereas, when extensive protection already exists, further reductions may require considerable expenditures. This relationship is illustrated by curve X in Fig.1. The curve U represents the total cost, and is the sum of curves X and Y.

**IV—8.** As stated in para.IV—4, the objective of radiation protection optimization is to maximize the net benefit to society of the practice with respect to expenditures made for radiation protection. This will be achieved at a level of protection $A'$ such that the total cost $U(S_A^c)$ is minimal. This is not equivalent to minimizing the cost of the detriment, Y. This latter process could result in a zero detriment, but only with the expenditure of enormous costs for radiation protection that could make the practice prohibitively expensive and economically unjustifiable.

**IV—9.** More important, the expenditure of resources to achieve a minimum detriment from radiation also would reduce the finite societal resources available for other forms of health protection and, therefore, could reduce the overall level of health protection (see para. IV—27).
DIFFERENTIAL COST-BENEFIT ANALYSIS

IV-10. The method of determining the optimal level of radiation protection is called differential cost-benefit analysis or cost-effectiveness analysis. Theoretically, the net benefit to society will be maximized.
when no additional net benefit is obtained from raising or lowering the collective dose commitment, \( S^c \). Differentiating Eq.(7) with respect to \( S^c \), this condition is achieved when

\[
\frac{dB}{dS^c} = \frac{dV}{dS^c} - \left( \frac{dP}{dS^c} + \frac{dX}{dS^c} + \frac{dY}{dS^c} \right) = 0
\]  

(9)

**IV—11.** The value of a practice to society, \( V \), and the cost of carrying out this practice (except for radiation protection expenditures), \( P \), should be independent of the level of protection and, consequently, independent of the collective dose commitment, therefore

\[
\frac{dV}{dS^c} = 0, \quad \text{and} \quad \frac{dP}{dS^c} = 0
\]

Equation (9) then reduces to the optimization of the radiation protection and health detriment costs to society,

\[
\frac{dB}{dS^c} = \frac{dX}{dS^c} + \frac{dY}{dS^c} = \frac{dU}{dS^c} = 0
\]  

(10)

and this is achieved at a value of \( S^c \) such that

\[
-\frac{dX}{dS^c} = \frac{dY}{dS^c}
\]  

(11)

**IV—12.** For practical applications, changes in protection levels are achieved in finite rather than infinitesimal increments, i.e. both \( X(S) \) and \( Y(S) \) are discreet step-functions, not continuous curves. In this case the differentials used above must be replaced by increments, i.e.
\[
\frac{\Delta B}{\Delta S^c} = 0 \quad \text{when}
\]

\[
- \frac{\Delta X}{\Delta S^c} = \frac{\Delta Y}{\Delta S^c}
\]  

(12)

These increments can be related to the incremental protection costs and incremental detriment costs associated with going from one level of protection A to another level of protection B, i.e.

\[
\Delta X = X_B - X_A
\]  

(13)

\[
\Delta Y = Y_B - Y_A
\]  

(14)

\[
\Delta S^c = S^c_B - S^c_A
\]  

(15)

The process of evaluating these incremental changes for the purpose of optimization is a differential cost-benefit analysis.

IV–13. For this process, we are always dealing with changes in X, Y, and S^c with respect to some reference level of protection. As discussed in para. I–18, for some dose increments above background one can assume a directly proportional relationship between the change in health detriment and the change in the collective dose commitment, regardless of any assumptions regarding the actual nature of the dose-effect relationship, except that the average dose from all sources of radiation exposure (including natural radiation) is above any threshold, if one were to exist. By a similar argument, it may be assumed that the incremental detriment cost, \(\Delta Y\), is directly proportional to the incremental collective dose commitment, \(\Delta S^c\),

\[
\Delta Y = \rho \Delta S^c
\]  

(16)

where \(\rho\) is the cost of health detriment associated with a unit increase in the collective dose commitment.
IV—14. In evaluating the collective dose commitment, the contribution from occupational radiation exposure should be considered as well as the exposure that would result from radioactive material released to the environment (see para. III—7). This will ensure that the collective dose commitment to the world population is truly optimized. When setting discharge limits based upon a differential cost-benefit analysis, it may be desirable to set the authorized release limits somewhat above the theoretical optimum to account for uncertainties in the analysis. This is particularly important for effluent treatment technology which has not been employed in actual full-scale operation. If an optimum value based upon limited experience is used, the release limit may be too restrictive to account for minor operational problems or the failure of equipment to work completely as predicted. Two approaches have been used to overcome this difficulty. One approach is to specify design objectives to which the plant should be designed, and then to set operating limits at somewhat higher levels to permit operational flexibility. This approach has been used by the US Nuclear Regulatory Commission [5] in its establishment of effluent limitations for light-water reactors. The operational limits permit operation up to one-half the annual design objective doses in any calendar quarter before corrective action is required. A second approach is to permit releases to exceed the authorized release limits for a limited period until appropriate corrective action can be taken. This may be accomplished by means of a variance issued by the cognizant regulatory agency. This approach has been used by the US Environmental Protection Agency in its establishment of environmental radiation standards for nuclear fuel cycle operations [6].

OPTIMIZED COLLECTIVE DOSE COMMITMENT

IV—15. Provided that the ICRP dose limits are met, the preceding analysis leads to an optimized situation resulting in an 'optimized
collective dose commitment'. It is therefore necessary to ensure that this collective dose commitment does not lead to average individual doses in the critical group of the population above the dose limits of the ICRP or those limits prescribed in national regulations.

**IV—16.** The method for implementation of this condition consists of comparing, on the one hand, the release $R_{k1}$ (see para. II—23) corresponding to the optimized collective dose commitment and, on the other hand, the release $R^*_k$ which would involve exposure of individuals in the critical group of the population at the dose limits. All ratios $R_{k1}/R^*_k$ then must be less than one. If this condition is not met, the release limits must be adjusted accordingly. This could result in release limits that depart from the optimum levels based solely on the cost-effective reduction of the collective dose commitment.

**DIFFERENTIAL COST-BENEFIT ANALYSIS AS APPLIED TO ONE SOURCE AND A LOCAL POPULATION**

**IV—17.** At a protection level, $A$, the dose commitment in a specified organ or tissue in population group $j$, resulting from one unit of practice, is $H_{jA}^c$, and the population size is $N_j$. The collective dose commitment $S_{jA}^c$ is

$$S_{jA}^c = N_j H_{jA}^c$$

and the corresponding detriment, $G_{jA}$, is (cf. para. I—18)

$$G_{jA} = S_{jA}^c \sum_i r_{ij} g_{ij}$$

**IV—18.** Following the application of additional radiation protection measures, which yield a new, higher, protection level $B$, the dose
commitment is $H_j^c B$, with the corresponding collective dose commitment $S_j^c B$, and detriment $G_j B$. The differential detriment cost, $\Delta Y$, is

$$\Delta Y = (G_j^A - G_j^B) \epsilon$$

where $\epsilon$ is the monetary value of one detriment unit and

$$\rho = \epsilon \sum_i r_{ij} g_{ij}$$

is the monetary value of one collective dose commitment unit. The differential cost of protection, $\Delta X$, is

$$\Delta X = X_A - X_B \quad \text{or} \quad \Delta X = X_B - X_A$$

since achieving better protection is generally more costly, so that $X_A < X_B$. As long as the differential cost of protection, $\Delta X$, is lower than the corresponding differential cost of detriment, $\Delta Y$, the effort to improve protection to protection level $\Delta B$ would be warranted.

IV–19. In the case where there is a large number of sources in one area, the additive dose due to the combined releases from these sources might be sufficient to exceed the ICRP dose limits for an individual in the critical group, unless further reductions are achieved. Such a situation might be envisioned, for example, when many reactor
sites are located along the same waterway, but in an area of low population density, where the (local or regional) collective dose would be low. See para. IV—16.

DIFFERENTIAL COST-BENEFIT ANALYSIS AS APPLIED TO MULTIPLE SOURCES AND THE WORLD POPULATION

IV—20. The method outlined in paras IV—17 and IV—18 applies to any population and any type of source, and may thus be applied to e.g. cases where several sources and the world population are considered. In such cases it is often necessary to start by considering the contributions from individual sources to properly defined sub-populations. This information is of interest per se, and it is also necessary for the subsequent analysis, as both the detriment cost term and the protection cost term are sums of contributions from a number of sources and sub-populations.

IV—21. The collective dose commitment at protection level A from source k, $S^c_{kA}$, is (see para. IV—17)

$$S^c_{kA} = \sum_j N_j H^c_{kjA}$$

and the corresponding detriment, $G_{kA}$, is

$$G_{kA} = S^c_{kA} \sum_i r_{ij} g_{ij}$$
Using the detriment values before and after optimization, the differential detriment cost, $\Delta Y$, is then calculated according to the procedure outlined in para. IV–18.

**IV–22.** When multiple sources have to be considered, the collective dose commitment $S_A^c$, and detriment $G_A$, at protection level $A$, are respectively

$$S_A^c = \sum_k S_{kA}^c$$

(22)

$$= \sum_k \sum_j N_j H_{kjA}$$

and

$$G_A = \sum_k G_{kA}$$

(23)

$$= \sum_k S_{kA}^c \sum_j r_{ij} g_{ij}$$

$$= \sum_k \sum_j N_j H_{kjA} \sum_i r_{ij} g_{ij}$$
The differential cost of detriment, \( \Delta Y \), is

\[
\Delta Y = (G_A - G_B) \varepsilon
\]

(24)

\[
= \sum_k \sum_j N_j (H_{kjA}^c - H_{kjB}^c) \varepsilon \sum_i r_{ij} g_{ij}
\]

\[
= \sum_k \sum_j N_j (H_{kjA}^c - H_{kjB}^c) \rho
\]

A special case of multiple sources is future sources. These have been dealt with in paras I–25 to I–27.

SPECIAL CONSIDERATIONS INHERENT IN THE APPLICATION OF COST-BENEFIT TECHNIQUES

IV–23. When comparing the differential cost of protection and the differential cost of detriment, a common quantity is required. A monetary quantity seems to be most universally applicable even though it raises problems. Evaluation of the detriment from radiation exposure therefore requires the quantification of the monetary cost of ill-health. The economic bases for quantifying the 'monetary value of human life' are developing [1–3] but the stigma of setting a monetary value on human life has not been resolved.

IV–24. The setting of optimal release limits for routine discharges of radioactive materials to the environment is conducted under the assumptions given in para. IV–1, i.e. that the radiation exposure resulting from a given practice is justifiable and that individual exposures
are within ICRP recommendations. The latter condition ensures that the incremental risk to individuals is small compared with the total risk that exists from natural hazards (disease, lightning, earthquakes, hurricanes, tornadoes, etc.) or man-made sources of health detriment (air pollution, public transportation system, structural failures etc.). Thus, for the setting of routine release limits one does not need to assess the ‘value of human life’, per se, but the cost of incremental reductions in life-span or incremental changes in survival probabilities.

IV—25. For low-level radiation dose below ICRP dose limits the effect is stochastic and the individual who would suffer the effect is unidentifiable. Whereas society may expend extraordinary resources to save a given identifiable individual, societal resources are finite and similar levels of expenditure are not made to save or protect the statistical unidentified individual.

IV—26. The finite nature of expenditures for current health protection or risk reduction provides a useful index for comparison, but these expenditures may not be strictly proportional to the collective detriment to the population as they are determined by political and social processes. Use has recently been made, however, of an assumed range of acceptable values for expenditures for risk reduction to establish radiation standards. Direct estimates have also been made of the value of the radiation detriment. Limited surveys have also been made of the worth that professionals in the radiation protection field would assign to a unit of collective dose (dollar/man \cdot rem). These

6 The US Environmental Protection Agency recently used a range of values for risk reduction of US $200,000 – US $500,000 per projected serious health effect eliminated, in establishing environmental radiation standards for normal releases from US facilities comprising the nuclear fuel cycle [6].

estimates apply only to uniform whole-body irradiation and equivalent estimates may be required for the cost of the detriment from collective dose commitments in other organs. These costs would be expected to be correspondingly smaller for other organs because of the lower detriment per rem for partial body irradiation (cf. para. I–18).

IV–27. Since the monetary value of radiation exposure reductions might vary among nations, national authorities might have to determine these values for their own population protection, but hopefully, an acceptable internationally agreed-on approach can be developed for global commitments. Care should be exercised when using a monetary value for the unit radiation detriment or unit collective dose commitment that it is not out of proportion to implicit or explicit values in use for other sources of health detriment. Clearly, more efforts are needed in this area in order to use these cost-benefit techniques to their greatest potential.

IV–28. All human activities involve some inequities in the distribution of benefits and detriments to different population groups. For example, the general public incurs the detriment from automobile emissions, and pedestrians are subjected to higher risks without receiving direct benefits. Similar situations exist for radiation exposure. For example, individuals residing near a fuel fabrication facility may not receive any of the primary benefits from this practice, i.e. the electric power generated by the fuel. Secondary benefits such as those deriving from tax payments by the facility might accrue to the local population, but the primary benefits from the practice might be only received by a distant group that does not receive any of the detriment. The release of long-lived radionuclides to the environment, as, for example, from spent fuel reprocessing plants could result in detriments received by the world’s population, while the primary benefits are received by only some groups in one nation. Lastly, the genetic detriments from radiation exposure will be received by future generations and not the immediate individuals receiving the primary benefits.
IV—29. These inequities in the distribution of benefits and detriments in society are mitigated by regulatory authorities which establish limits on individual activities (air pollution emission criteria, traffic safety regulations, etc.), so that no group is subjected to excessive detriment. For radioactive material releases, the use of the collective detriment concept, that is the global collective dose commitment, and the maintenance of all individual exposures within the ICRP limits, will ensure that the detriments are considered in the justification of the activity and that no single group will bear a severe detriment.

REFERENCES TO CHAPTER IV


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LIST OF BASIC TERMS USED

Note: The term *dose* as used in this report means *dose equivalent* unless qualified otherwise.

Collective dose rate:

The weighted product of dose rate and number of individuals in a given population

\[ \dot{S}(t) = \int_{0}^{\infty} \dot{H} N_{\dot{H}}(\dot{H},t) \, d\dot{H} \]

where \( N_{\dot{H}}(\dot{H},t) \) is the population distribution in dose rate, \( N_{\dot{H}}(\dot{H},t) \, d\dot{H} \) being the number of individuals receiving a dose rate in a specified organ or tissue in the range \( \dot{H} \) to \( \dot{H} + d\dot{H} \) at time \( t \). The collective dose rate can also be assessed by the expression

\[ \dot{S}(t) = \sum_{j} \bar{H}_{j} N_{j}(t) \]

where \( \bar{H}_{j} \) is the per caput dose rate in a population group \( j \), and \( N_{j}(t) \) is the size of that group as a function of time, \( t \). \( \dot{S}(t) \) as used in this report denotes the collective dose equivalent rate.
LIST OF BASIC TERMS USED

Absorbed dose commitment and dose equivalent commitment:

For any specified decision, practice or operation, the infinite time integral of the per caput absorbed dose rate or the average dose equivalent rate caused by that decision, practice or operation in a specified population is:

\[ D^c = \int_{0}^{\infty} \bar{D}(t) \, dt \]

or

\[ H^c = \int_{0}^{\infty} \bar{H}(t) \, dt \]

where \( \bar{D}(t) \) is the average absorbed dose rate and \( \bar{H}(t) \) is the per caput dose equivalent rate.

Collective absorbed dose commitment and collective dose equivalent commitment:

For any specified decision, practice or operation, the infinite time integral of the product of the per caput absorbed dose rate \( \bar{D}(t) \) caused by that decision, practice or operation in a specified population and the size \( N(t) \) of that population:

\[ S^{cD} = \int_{0}^{\infty} \bar{D}(t) \, N(t) \, dt \]
If alternatively $\bar{H}(t)$ is used in the calculation, the collective dose equivalent commitment is obtained:

$$S^c \bar{H} = \int_{0}^{\infty} \bar{H}(t) \cdot N(t) \cdot dt$$

Note: In this report $S^c$ for convenience will mean collective dose equivalent commitment.

**Annual dose limit:** Any of the annual dose equivalent limits for individual members of the public recommended by the ICRP as part of its system of dose limitation (Ref. [7], Chapter I).

**Derived limit:** Values of measurable quantities, in a given, simplified exposure model, corresponding to the dose limits recommended by the ICRP. Many of the measurements made in a monitoring programme cannot be expressed directly in terms of dose for comparison with the ICRP dose limits. In these circumstances, the use of simplified exposure models can provide quantitative links between the measured quantities and the dose limits recommended by the ICRP. Due to conservatism in selecting the exposure models, the adherence to a derived limit provides virtual certainty of compliance with the ICRP dose limits.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authorized limit:</td>
<td>Limit actually set by the authorities, for a given source or a given environment, and which may or may not be derived from the ICRP dose limits.</td>
</tr>
<tr>
<td>Action level:</td>
<td>Environmental level specified in advance that has been determined to justify remedial action on the basis of knowledge that resulting exposures of people would otherwise be greater than is necessary or desirable.</td>
</tr>
<tr>
<td>Critical group:</td>
<td>For a given source or group of sources, the group of members of the population, whose exposure is homogeneous and typical of the individuals receiving the highest dose.</td>
</tr>
<tr>
<td>Cost-benefit analysis:</td>
<td>A systematic examination of the positive attributes (benefits) and negative effects (costs) of undertaking an action. For the purpose of this report, cost-benefit analysis is reserved for the justification of the source of radiation exposure.</td>
</tr>
<tr>
<td>Differential cost-benefit analysis: or</td>
<td>A sequential analysis of the incremental changes in costs and benefits between alternative actions. As used in this report, it represents the approach for optimizing radiation protection expenditures and defining 'as low as reasonably achievable' for radiation exposure limitation.</td>
</tr>
<tr>
<td>Differential cost-effectiveness analysis:</td>
<td></td>
</tr>
<tr>
<td>Detriment</td>
<td>The detriment in a population is the mathematical expectation of harm incurred from a collective dose commitment taking into account not only the probabilities of each type of deleterious effects but the severity of the effect as well.</td>
</tr>
</tbody>
</table>
IMPORTANT SYMBOLS

Note: The units rad for absorbed dose and rem for dose equivalent have been used throughout this report. The SI units for these quantities are the gray (Gy) and the sievert (Sv), respectively. $1 \text{ Gy} = 10^2 \text{ rad}$; $1 \text{ Sv} = 10^2 \text{ rem}$.

\[ \begin{align*}
D & \quad \text{absorbed dose (rad)} \\
\bar{D} & \quad \text{per caput absorbed dose (rad)} \\
\dot{D} & \quad \text{absorbed dose rate (rad/unit of time)} \\
D_c & \quad \text{absorbed dose commitment (rad)} \\
H & \quad \text{dose equivalent (rem)} \\
\bar{H} & \quad \text{per caput dose equivalent (rem/unit of time)} \\
\dot{H} & \quad \text{dose equivalent rate (rem/unit of time)} \\
H_c & \quad \text{dose equivalent commitment (rem)} \\
S & \quad \text{collective dose equivalent (man} \cdot \text{rem)} \\
\dot{S} & \quad \text{collective dose equivalent rate (man} \cdot \text{rem/unit of time)} \\
S_P & \quad \text{collective absorbed dose (man} \cdot \text{rad)} \\
\dot{S}_P & \quad \text{collective absorbed dose rate (man} \cdot \text{rad/unit of time)} \\
S_c & \quad \text{collective dose equivalent commitment} \\
S_{cD} & \quad \text{collective absorbed dose commitment (man} \cdot \text{rad)} \\
l & \quad \text{radionuclide} \\
k & \quad \text{source (practice, event)} \\
j & \quad \text{group of individuals} \\
m & \quad \text{organ}
\end{align*} \]
IMPORTANT SYMBOLS

i deleterious effect
\[ p_i \] probability of suffering effect \( i \)
\[ r_i \] risk factor for effect \( i \)
\[ g_i \] weighting factor for severity of effect \( i \)
\( t \) time
\( G \) detriment
\( N \) population size
\( N_j \) size of population group \( j \)
ADL Appropriate ICRP annual dose equivalent limit
DL derived limit; (previously denoted as DWL)
MPC maximum permissible concentration
\( R \) activity release into the environment
\( R_{k|i} \) activity release of nuclide \( i \) from source \( k \)
\( R^* \) activity release corresponding to ICRP dose limit
\( u \) environmental compartment
\( v \) environmental compartment
\( C_u \) concentration in environmental compartment \( u \)
\( C_{lv} \) average level (concentration) of nuclide \( l \) in compartment \( v \)
\( f_d \) dose factor (e.g. man·rad/Ci)
\( f_{uv} \) transfer factor relating time integral of concentration in compartment \( v \) to that in compartment \( u \)
\( f_{jkl} \) factor relating the dose commitment from nuclide \( l \) in population group \( j \) to a unit activity release from source \( k \)
\( \epsilon \) monetary equivalent of one detriment unit (monetary unit/health effect)
\( \rho \) monetary equivalent of one collective dose commitment unit (monetary unit/man·rem)
\( Z \) rate at which additional nuclear power production is made available (MW(e)/unit of time)
\( \theta \) age of individual in cohort
$N_\theta(\theta,t)$ number of individuals of a cohort having an age $\theta$ at time $t$

$\Omega$ weighting factor for computation of genetically significant dose or for biologically relevant dose

$H_{wb,L}$ is the ICRP recommended annual dose equivalent limit for uniform irradiation of the body, namely 5 rem per year

$w_m$ weighting factor given in ICRP Publication 26, representing the proportion of the stochastic risk resulting from exposure of tissue or organ $m$ to the total risk, when the whole body is irradiated uniformly

$H_m$ is the dose equivalent in tissue or organ $m$
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Appendix 1

EXPLANATION AND APPLICATION
OF THE CONCEPT
OF COLLECTIVE DOSE COMMITMENT

A.1-1. The purpose of this Appendix is to explain the background
of the mathematical formulation of the collective dose commitment in a
more illustrative way than merely by the mathematical formulae and to
describe the different purposes for which the concept may be applied.

A.1-2. The two quantities absorbed dose or dose rate and dose
equivalent or dose equivalent rate are "intensive"\(^8\) quantities. It is there­
fore not meaningful to add, for example, the absorbed dose or dose rate
in one person to the absorbed dose or dose rate in another person. It is,
however, meaningful to derive the weighted product of absorbed dose
or dose rate to individuals in a population and number of individuals in
that population, thus in the case of collective absorbed dose rate, \(\hat{S}^D\),

\[
\hat{S}^D = \int_{0}^{\infty} \hat{D} N^D(D) \, d\hat{D}
\]

where \(N^D(D)\) is the population spectrum in absorbed dose rate,
\(N^D(D) \, d\hat{D}\) being the number of individuals receiving an absorbed dose

---

\(^8\) The temperature of a system is an intensive quantity, and cannot be added
to the temperature of another system to obtain the overall temperature of the
combined systems. However, the quantity of heat in each system is an extensive
quantity and can be added to obtain the overall quantity of heat in the combined
systems.
rate in the range $\dot{D}$ to $\dot{D} + d\dot{D}$. This weighted product is called the collective absorbed dose rate and is expressed in man\cdot rad per unit time. Similarly, a collective dose equivalent rate, expressed in man\cdot rem per unit time can be defined.

**A.1—3.** The collective absorbed dose rate (or collective dose equivalent rate) is an 'extensive' quantity and can, conceptually, apply even in the extreme example of a population of one person. If a person receives a dose rate of $A$ rad per unit time, it may be said that he has also received a collective dose rate of $S$ man\cdot rad per unit time numerically equal to $A$. The calculation of the collective dose rate for a group of people may therefore be considered to be the addition of the individual collective dose rates (which can be added because collective dose rate is an extensive quantity), rather than the addition of their individual dose rates (which cannot strictly be added because dose rate is an intensive quantity).

**INTEGRATION OF COLLECTIVE DOSE RATE IN SPACE**

**A.1—4.** There are two obvious applications of collective dose rate. One is as an intermediate step in the calculation of the average dose rate in a population. The normal definition of an average leads to the expression

$$
\bar{\dot{D}} = \frac{\int_{0}^{\infty} \dot{D} N_{\dot{D}} \, d\dot{D}}{\int_{0}^{\infty} N_{\dot{D}} \, d\dot{D}}
$$
and since
\[
\int_{0}^{\infty} N \cdot d \bar{D} = N,
\]
i.e. the total number of population, it follows that
\[
\bar{D} = \frac{\bar{S}^{D}}{N} \quad \text{and similarly} \quad \bar{H} = \frac{\bar{S}^{H}}{N}
\]

A.1—5. The other application follows from the assumption that the rate of harmful late effects (cancer and hereditary disease) in a population is directly proportional to both the number of persons exposed and to the average dose rate. Therefore the rate of harmful effects, \( \dot{M} \), is also proportional to the collective dose rate
\[
\dot{M} = r \cdot N \cdot \bar{D} = r \dot{S}
\]
The proportionality constant \( r \) is the 'risk factor', i.e. the expected rate of cases per unit collective dose rate. To the extent that the quality factors recommended by the ICRP will be assumed to reflect the true RBE, the dose equivalent may be more appropriate to use in this assessment than the absorbed dose. The collective dose equivalent rate may therefore be considered as a very approximate measure of the harm rate from any given exposure pattern.

A.1—6. The total collective dose rate from an event (e.g. a unit of practice) can be taken to be a measure of the total harm rate from that event. The assessment of the total collective dose rate from the event requires that all individuals receiving a dose rate from that event be considered. As the integral defining the collective dose rate remains
unchanged if the population is made arbitrarily larger than the actual exposed group, the requirement of completeness can be ensured by defining the population as the world population.

**A.1—7.** In other applications, however, radiation protection measures may be guided by the knowledge of whether the major part of the collective dose rate is caused by local exposures rather than by global exposures. It is convenient to sub-divide the world population into several groups $j$, so that the collective dose rate will be the sum of the contributions from each of these groups:

$$
\dot{S}^D = \sum_j \dot{S}_j = \sum_j \int_0^\infty \dot{D} N_j(\dot{D}) \ d\dot{D}
$$

where $N_j(\dot{D})$ is the population spectrum in dose rate of group $j$; $\dot{S}^H$ can in a similar way be calculated.

### INTEGRATION OF COLLECTIVE DOSE RATE IN TIME

**A.1—8.** The two applications of collective dose rate mentioned in paras A.1—4 and A.1—5, respectively, imply that a practice which will cause persisting environmental contamination cannot be assessed merely by the collective dose rate at any one given time. It will be necessary to integrate over time as well as over space, or in simpler terms: the collective doses for each future year will have to be added.

**A.1—9.** This addition becomes complicated if a number of the involved quantities vary with time, e.g. the contamination levels and their persistence at different locations, the age and therefore the metabolic response of the exposed individuals, the number of individuals in various age groups, etc. It may be helpful to illustrate the basic principle,
however, with an example in which these complications are less severe: a global uniform contamination with a gamma-emitting, long-lived noble gas. In this case we will assume that the dose rate will be the same for each individual exposed at the same time, irrespective of sex and age. The collective dose rate will then simply be the product of individual dose rate and number of people in the world population. To illustrate the time integration we may therefore simplify the problem by looking at the exposure of a population of one person. It will be useful, however, not to consider any identifiable individual but a ‘position’ which will be occupied by a succession of individuals over the years. This will be a justifiable approach if we wish to assess the total future harm from the practice causing the persisting contamination. The situation is illustrated by the schematic representation in Fig.2.

A.1—10. In the simplified example in Fig.2(a) it has been assumed that a practice of unit magnitude during any one year will give rise to an environmental pollution which will cause radiation doses during some years to follow. The annual doses have been assumed to be A (rad or rem) during the year of practice, B, C, D and E during the first, second, third and fourth year after the practice, respectively. The dose commitment from one year’s practice is in this case the sum of all the future doses, i.e. A + B + C + D + E.

A.1—11. If the practice is repeated during one more year, a similar sequence of doses is superimposed on the doses from the first year’s practice. If the practice continues, a steady state situation will eventually be reached, when the annual addition of radioactive material to the environmental pollution is compensated by the radioactive decay of the contaminating nuclides and their removal (e.g. by sedimentation) from the biosphere. It is seen from Fig.2(c) that the annual dose when the steady state has been reached is composed by the dose from the practice during any one year plus the dose from the practice during the preceding years, i.e. A + B + C + D + E. This is equal to the dose commitment from one year of practice. It follows that the future average annual dose
FIG. 2. Dose commitment (a) from first year’s practice $A + B + C + D + E$, (b) from second year’s practice (shaded area) $A + B + C + D + E$, (c) under steady state conditions.
CONCEPT OF COLLECTIVE DOSE COMMITMENT

within any given population (e.g. the critical group or the world population) can therefore be kept within any postulated limit for that population as long as the dose commitment for each year of practice is kept within the same limit.

A.1–12. It can also be seen from Fig. 2(b) that a practice which is only in existence during a limited period, \( \tau \), shorter than the lifetime of the pollution in the environment, will never give rise to a steady state situation. The maximum annual dose, at the end of the practice, is equal to the 'limited' dose commitment which is obtained if the summation is only carried out over the period of practice. In the illustrated example of two years of practice, the maximum annual dose will be \( A + B \), which is also the sum of the annual doses from one year’s practice, if the summation is only carried out over two years.

A.1–13. It is seen from this example that the dose commitment, with unrestricted summation over all future years, may be used both to give a measure of the total future harmful effect of each year of practice and to indicate the annual future dose if the practice continues long enough to give rise to steady state conditions. The limited dose commitment, with summation over a period of the same length as the period of practice, will indicate the maximum annual dose at the end of the practice.

A.1–14. In the previous example it was assumed that all individuals would be subject to the same dose rate from external exposure at any given time, and 'dose commitment' was not given any strict definition. The situation becomes much more complicated if the radiation exposure is due to radioactive substances which are taken into the body and are retained in body tissues over many years. This situation may first be illustrated by a situation where it is of interest to assess the lifetime collective dose to a group of people who live in the same environment but who may receive different radiation doses because of exposures at different times and at different ages.
A.1—15. The most immediate approach would be to assess the lifetime collective dose to each cohort\(^9\) of individuals. If \(D_u\) denotes the lifetime collective absorbed dose of persons born in year \(u\), and \(N_u\) denotes the number of persons in the cohort, the collective absorbed dose contribution from each cohort will be \(S^D_u = N_u D_u\). The total collective absorbed dose due to the originating event (e.g. one year of practice) would be the sum of the cohort collective absorbed doses from cohorts of persons born so early that they just only survive the event, to cohorts of persons to be born in the distant future:

\[
\sum_u S^D_u = \sum_u N_u D_u \quad \text{and similarly}
\]

\[
\sum_u S^H_u = \sum_u N_u H_u
\]

The same calculation can be made for each region of the environment having a uniform contamination. If, in a similar way to the sub-division made in para. A.1—7, the global population is sub-divided into sub-groups, \(j\), with uniform contamination, again the total global collective dose would be the sum of the contributions from such sub-groups:

\[
\sum_j \sum_u S^D_{ju} = \sum_j \sum_u N_{ju} D_{ju}
\]

\(^9\) For the purpose of this document, 'cohort' denotes groups of persons with the same year of birth.
A.1—16. To simplify the presentation, for illustrative purposes, it may suffice to describe the situation in any one of these sub-groups. Each cohort of persons will receive individual lifetime absorbed doses, $D_u$, which can be obtained as the integral over the cohort lifetime of the dose rate, $\dot{D}_u(t)$, in the cohort. The functions $\dot{D}_u(t)$ will have different shapes for different values of $u$ and similarly the function $\dot{H}_u(t)$. This is illustrated for a purely hypothetical example in Fig.3.

A.1—17. For the example in Fig.3 it has been assumed that the practice at time $t = 0$ gives rise to an environmental contamination which slowly decreases because of radioactive decay and material becoming
Time dependence of contamination

\[ \hat{\dot{y}}(t) \]

\[ \text{TIME} \]

FIG. 4. Collective dose rate.

less available for routes to man, but which will last for some hundred years. The decrease of this contamination is indicated by the dashed curve in the figure.

A.1–18. Cohorts with birth years \( u < 0 \) will have shorter exposure times than cohorts with \( u > 0 \). Cohorts with \( u \sim 0 \) will accumulate the highest lifetime doses. In the example, the maximum dose rates are found in individuals of high age. The derivation of the likely time functions \( \hat{D}_u(t) \) or \( \hat{H}_u(t) \) is a difficult task and the metabolic information is sometimes insufficient. In principle, however, the total collective dose from the practice will be obtained by the summation shown in para. A.1–15, i.e. by summation over cohorts and over sub-groups with different levels of contamination. This total collective dose is composed of all contributions caused by the practice which will occur in the future, after the practice. It is therefore the collective dose commitment of the practice.
A.1—19. There is a less obvious, but often more convenient way of assessing this collective dose commitment. This is illustrated in Fig.4. For each given sub-group of the world population (cf. para. A.1—15) it is possible to define, at any specified time, the collective dose rate for the sub-group. It is therefore possible to derive the function $\dot{S}(t)$, i.e. the collective dose rate as a function of time. If this function is integrated over infinite time, the integral is the collective dose commitment to this population sub-group from the practice. Formally, the calculation is identical to the summation of cohort doses in the sub-group as described in paras A.1—15 to A.1—19. This is shown, for example, in the 1969 report by UNSCEAR (paras 35—52)$^{10}$, where a more rigorous mathematical formulation has been elaborated to show that the two modes of calculation are the same. This method is not readily applied, however, to the calculation of collective dose commitments when the population considered varies in size as a function of time. It can, however, be used to estimate the per caput dose commitment in such cases (see para. I—22).

A.1—20. The derivation of $\dot{S}(t)$ at any given time $t$ involves a summation of collective dose rates to individuals of different sex and age and therefore also with different metabolic characteristics, resulting in different individual dose rates in one and the same environment. The derivation of lifetime cohort doses as described earlier was a crude approximation of the biologically relevant exposures. In theory, various weighting factors could be introduced to account for different child expectancy (in relation to gonadal exposures) or long latency periods for cancer induction. With the procedure described in para. A.1—19, such weighting may be introduced before the summation of individual collective doses.

A.1—21. At any specified time $t$, the weighted average individual absorbed dose rate in the selected population sub-group is defined by:

$^{10}$ See Ref. [18], Chapter I.
where \( \Omega(\theta) \) is the weighting factor for biological relevance as a function of age, \( \theta \), \( N_\theta(\theta,t) \) is the number of individuals of age \( \theta \) at time \( t \), and \( \dot{D}(\theta,t) \) is the individual absorbed dose rate in individuals of age \( \theta \) at time \( t \) (see Fig.5). Since the collective absorbed dose rate is

\[
\dot{S}(t) = N(t) \overline{\dot{D}(t)}
\]

\[
= \int_0^\infty N_\theta(\theta,t) \, d\theta \overline{\dot{D}(t)}
\]

it follows that

\[
\dot{S}^D(t) = \int_0^\infty \Omega(\theta) \, N_\theta(\theta,t) \, \dot{D}(\theta,t) \, d\theta
\]

and similarly

\[
\dot{S}^H(t) = \int_0^\infty \Omega(\theta) \, N_\theta(\theta,t) \, \dot{H}(\theta,t) \, d\theta
\]
A.1—22. In the case of long-lived atmospheric contaminants it may well be that the major contribution to the global collective dose commitment is due to the global rather than to the local contamination. The latter may give higher individual doses, but to much fewer individuals and over a shorter period of time. The two components of $\hat{S}(t)$ — i.e. local and global — may be schematically illustrated by the curves in Fig.6.

A.1—23. For the purpose of controlling future exposures, it is usually not the main objective to limit the collective doses but rather to make certain that individual doses will remain below agreed limits. For this purpose it is preferable to assess dose commitments rather than collective dose commitments. The dose commitment is the infinite time integral of the average dose rate in the given population. As in the example given in para.A.1—9, it will not be necessary to let it relate to
a population of identifiable individuals. It is of greater interest to relate it to a geographically or otherwise defined group having something in common, e.g. the critical group, the local population, the global population. For such a group the rule will always be that the dose commitment from one year of practice will be equal to the annual dose under steady state conditions, irrespective of the size of the group.

A.1—24. If the purpose is to assess the future average annual individual dose at the time when it is highest, it will suffice to assess the integral of the average dose rate over a period of the same length as the practice, as was illustrated in Fig.2. This controlling time integral is sometimes called the ‘incomplete’ dose commitment, which may be misleading since nothing relevant to the objective has been omitted.

A.1—25. On the other hand, for the purpose of assessment of the total harm from a given practice, the full collective dose commitment from that practice will have to be calculated. For radionuclides for which no reliable assumption on the time functions $S(t)$ can be made, upper limits can be obtained on the assumption that only radioactive decay will make the radionuclide disappear from the relevant sector of the biosphere. This calculation requires a further assumption on the variation of the population size with time.
A.1—26. In the previous discussion it has been assumed that the practice will continue at constant rate over the total period, $\tau$, of practice. This is not likely to be the case, since many practices are rapidly expanding and will not be expected to cease abruptly but to decrease gradually. It may therefore be convenient to base the calculations on some other unit of practice than one year of operation. In the case of electric power production, the unit practice may be taken to be the production of one MW·a electrical energy.
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Appendix 2

DISCHARGE LIMITATIONS BASED ON CONCENTRATION INDICES [5, 37–39]<sup>11</sup>

A.2–1. Discharge control is in many cases implemented by setting maximum permissible concentrations for the receiving media. Such concentration values are usually derived from broad generalizations about human exposure pathways not supported by any detailed investigations of the particular environmental circumstances. As a form of control, whilst perhaps adequate in relation to single type exposure pathways of a relatively simple nature, such as drinking water quality criteria or those for respirable air, it is grossly inadequate to take effective account of food chain situations or of some situations pertaining to external exposure pathways.

A.2–2. The method rests on the assumption that concentration in the effluent at the time of discharge can be set, taking account of reasonable generalizations about likely dilution and subsequent reconcentration in various environmental compartments, such that exposure rates based on dose limits for members of the public cannot be exceeded. It is therefore based on a priori assumptions about the nature of the environment to which the nuclides are to be introduced, and about their likely behaviour when introduced. In many cases it will contain large margins of safety, but occasions will arise, where particularly limiting circumstances lead to dose limits being exceeded [5]. In practice, this approach is widely used to derive regulatory release limitations that may be applied at the effluent source. Such use should be generally employed only where large margins of safety are built into the assumptions used to derive the discharge limits, and these may lead to heavy expenditure on

<sup>11</sup> Reference numbers refer to the list of References to Chapter II, p.35.
effluent treatment in relation to the radiation exposure reductions achieved. The costs of conducting a critical pathway analysis will in most cases prove much cheaper and will lead to reasonable estimates of the actual radiation doses incurred which cannot be achieved by this approach.

SPECIFIC ACTIVITY APPROACH

A.2–3. This method, details of which appear in several publications [5,6,40–42], stems from a knowledge of the human organ or body burden of a radionuclide required to achieve the recommended ICRP dose limit [2,30]. The organ burden is then expressed as a maximum specific activity, i.e. as a relation between the organ burden and the concentration of the stable nuclide of the same element (or an element of similar physiological behaviour) in that organ or the body, namely pCi/g of the stable element. This specific activity becomes the limiting activity ratio for the recipient medium, air, soil or water, on the assumption that, if this ratio is not exceeded in the medium, it cannot be exceeded at any point in the food chain or in the critical organ in man. The rate of introduction of activity is set such that this ratio cannot be exceeded in the recipient medium.

A.2–4. The approach is attractive because it dispenses with the concentration factor data required in the pre-operational use of critical pathway techniques and is applicable regardless of the eating habits of the exposed individuals, and thus dispenses with the habits survey data required by the critical path approach. It is particularly applicable to food chain and drinking water evaluations and it cannot be used to limit the dose to the GI tract of exposed individuals. Furthermore, care must be exercised in its application to ensure that no excessive radiation exposure is incurred via external exposure pathways or during the transit through the GI tract of non-metabolized radionuclides.
A.2—5. The use of a stable nuclide distribution as an analogue for the distribution of a radionuclide involves a number of simplifying assumptions, principally that transfer factors for the two nuclides will be similar, e.g. biological availability and deposition. The major limitations imposed by most radionuclide releases to the environment will relate to concentrations achieved in the environment close to the point of release where it is most unlikely that the freshly introduced radionuclide will be in the same physico-chemical state as the stable nuclide and will therefore behave like, or assume the same distribution as, its stable counterpart.

A.2—6. The method has been successfully applied to the control of strontium-90 in the pasture-milk pathway because of the acceptable degree of chemical similarity between this radionuclide and calcium. However, a great deal more information is required on trace element distribution and behaviour in the natural environment before the method could be more widely applied.

TOTAL SYSTEMS ANALYSIS APPROACH [43,44]

A.2—7. This method requires a large volume of data on the relevant environmental parameters including transfer rates between all compartments eventually leading to human radiation exposure via either internal or external routes. It also requires a sophisticated computational system in order to provide adequate treatment of all the complexities involved in assessing all possible routes of exposure. Ultimately it will distinguish a few routes of exposure which will merit the most careful control and, by so doing, will result in a system similar to that arrived at by critical path analysis. However, much simpler considerations can lead to the early elimination of extraneous pathways from an assessment exercise, and it may at this time be regarded as an often unnecessarily complex and expensive procedure. If the method eventually becomes cheaper
and easier to use as relevant data and calculational techniques are built up and ready at hand, then it offers the advantage of rapid reassessment of the overall situation as changes in the model's input parameters occur.

A.2–8. On a local basis, its chief use will be in pre-operational exercises. Once an environment is labelled, it may be easier and more convincing to assess the situation in real terms through environmental measurements that will demonstrate the validity or conservatism of the model. The use of this approach is increasing for assessment on a regional and global basis, particularly for time integral projections of greater complexity which may involve multiple sources.
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The following conversion table is provided for the convenience of readers

**FACTORS FOR CONVERTING SOME OF THE MORE COMMON UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI) EQUIVALENTS**

**NOTES:**
(1) SI base units are the metre (m), kilogram (kg), second (s), ampere (A), kelvin (K), candela (cd) and mole (mol).
(2) ► indicates SI derived units and those accepted for use with SI;
    ▼ indicates additional units accepted for use with SI for a limited time.
(3) The correct symbol for the unit in column 1 is given in column 2.
(4) * indicates conversion factors given exactly; other factors are given rounded, mostly to 4 significant figures:
    [ ] in columns 3+4 enclose factors given for the sake of completeness.

| Column 1 | Multiply data given in: | Column 2 | Column 3 | Column 4 | to obtain data in:
|----------|-------------------------|----------|----------|----------|----------------------
| Radiation units |  |  |  |  |  |
| becquerel | 1 Bq | (has dimensions of s⁻¹) | 1.00 x 10⁶ Bq |  |  |
| disintegrations per second (= dis/s) | 1 s⁻¹ |  | 1.00 x 10⁶ Bq |  |  |
| ▼ curie | 1 Ci |  | 3.70 x 10¹⁰ Bq |  |  |
| ▼ roentgen | 1 R |  | 2.58 x 10⁸ C/kg |  |  |
| ▼ gray | 1 Gy |  | 1.00 x 10¹² J/kg |  |  |
| ▼ rad | 1 rad |  | 1.00 x 10⁻² Gy |  |  |
| ▼ sievert (radiation protection only) | 1 Sv |  | 1.00 x 10⁻¹ J/kg |  |  |
| ▼ rem (radiation protection only) | 1 rem |  | 1.00 x 10⁻² Sv |  |  |
| Mass |  |  |  |  |  |
| ▼ unified atomic mass unit (1/12 of the mass of ¹²C) | 1 u |  | 1.66057 x 10⁻²³ kg, approx. |  |  |
| ▼ tonne (= metric ton) | 1 t |  | 1.00 x 10³ kg |  |  |
| pound mass (avoirdupois) | 1 lbm |  | 4.536 x 10⁻¹ kg |  |  |
| ounce mass (avoirdupois) | 1 ozm |  | 2.835 x 10⁻² g |  |  |
| ton (long) (= 2240 lbm) | 1 ton |  | 1.016 x 10³ kg |  |  |
| ton (short) (= 2000 lbm) | 1 short ton |  | 9.072 x 10² kg |  |  |
| Length |  |  |  |  |  |
| statute mile | 1 mile |  | 1.609 x 10⁶ km |  |  |
| ▼ nautical mile (international) | 1 n mile |  | 1.852 x 10⁶ km |  |  |
| yard | 1 yd |  | 9.144 x 10⁻¹ m |  |  |
| foot | 1 ft |  | 3.048 x 10⁻² m |  |  |
| inch | 1 in |  | 2.54 x 10⁻² mm |  |  |
| mil (= 10⁻³ in) | 1 mil |  | 2.54 x 10⁻² mm |  |  |
| Area |  |  |  |  |  |
| ▼ hectare | 1 ha |  | 1.00 x 10⁴ m² |  |  |
| ▼ barn (effective cross-section, nuclear physics) | 1 b |  | 1.00 x 10⁻²⁸ m² |  |  |
| square mile, (statute mile)² | 1 mile² |  | 2.590 x 10⁶ km² |  |  |
| acre | 1 acre |  | 4.047 x 10³ m² |  |  |
| square yard | 1 yd² |  | 8.361 x 10⁻¹ m² |  |  |
| square foot | 1 ft² |  | 9.290 x 10⁻² m² |  |  |
| square inch | 1 in² |  | 6.452 x 10⁻⁴ mm² |  |  |
| Volume |  |  |  |  |  |
| ▼ litre | 1 L |  | 1.00 x 10⁻³ m³ |  |  |
| cubic yard | 1 yd³ |  | 7.646 x 10⁻¹ m³ |  |  |
| cubic foot | 1 ft³ |  | 2.832 x 10⁻² m³ |  |  |
| cubic inch | 1 in³ |  | 1.639 x 10⁻⁴ mm³ |  |  |
| gallon (imperial) | 1 gal (UK) |  | 4.546 x 10⁻³ m³ |  |  |
| gallon (US liquid) | 1 gal (US) |  | 3.785 x 10⁻³ m³ |  |  |

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</tr>
<tr>
<td>dyne per square centimetre</td>
<td>1 dyn/cm(^2) = 1.00 X 10^{-1} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>feet of water (4°C)</td>
<td>1 ftH(_{2})O = 2.989 X 10^{3} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inches of mercury (0°C)</td>
<td>1 inHg = 3.386 X 10^{2} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>inches of water (4°C)</td>
<td>1 inH(_{2})O = 2.491 X 10^{2} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kilogram force per square centimetre</td>
<td>1 kgf/cm(^2) = 9.807 X 10^{2} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pound force per square foot</td>
<td>1 lbf/ft(^2) = 4.788 X 10^{1} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pound force per square inch (= psi) (^c)</td>
<td>1 lbf/in(^2) = 6.895 X 10^{3} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>torr (0°C) (= mmHg)</td>
<td>1 torr = 1.333 X 10^{2} Pa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy, work, quantity of heat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>joule (= W·s)</td>
<td>1 J = 1.00 X 10^{7} N·m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electronvolt</td>
<td>1 eV = 1.602 19 X 10^{-19} J, approx.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>British thermal unit (International Table)</td>
<td>1 Btu = 1.055 X 10^{4} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calorie (thermochemical)</td>
<td>1 cal = 4.184 X 10^{3} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calorie (International Table)</td>
<td>1 cal(_{IT}) = 4.187 X 10^{3} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>erg</td>
<td>1 erg = 1.00 X 10^{-7} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>foot-pound force</td>
<td>1 ft·lbf = 1.336 X 10^{3} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kilowatt-hour</td>
<td>1 kW·h = 3.60 X 10^{6} J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kiloton explosive yield (PNE) (= 10^{12} g-cal)</td>
<td>1 kt yield = 4.2 X 10^{12} J</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Pa (g): pascals gauge  
\(^b\) atm (g) (= atu): atmospheres gauge  
\(^c\) lbf/in\(^2\) (g) (= psig): gauge pressure

Pa abs: pascals absolute  
atm abs (= ata): atmospheres absolute  
lbf/in\(^2\) abs (= psia): absolute pressure
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiply data given in:</td>
<td>by:</td>
<td>to obtain data in:</td>
<td></td>
</tr>
</tbody>
</table>

**Power, radiant flux**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>watt</td>
<td>1 W</td>
<td>( \equiv 1.00 \times 10^0 ) J/s</td>
</tr>
<tr>
<td></td>
<td>British thermal unit (International Table) per second</td>
<td>1 Btu/s</td>
<td>( = 1.055 \times 10^4 ) W</td>
</tr>
<tr>
<td></td>
<td>calorie (International Table) per second</td>
<td>1 cal(_{IT})/s</td>
<td>( = 4.187 \times 10^4 ) W</td>
</tr>
<tr>
<td></td>
<td>foot-pound force/second</td>
<td>1 ft( \cdot )lbf/s</td>
<td>( = 1.356 \times 10^4 ) W</td>
</tr>
<tr>
<td></td>
<td>horsepower (electric)</td>
<td>1 hp</td>
<td>( = 7.46 \times 10^2 ) W</td>
</tr>
<tr>
<td></td>
<td>horsepower (metric) (= ps)</td>
<td>1 ps</td>
<td>( = 7.355 \times 10^2 ) W</td>
</tr>
<tr>
<td></td>
<td>horsepower (550 ft( \cdot )lbf/s)</td>
<td>1 hp</td>
<td>( = 7.457 \times 10^2 ) W</td>
</tr>
</tbody>
</table>

**Temperature**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>degrees Celsius, ( t )</td>
<td>( t = T - T_0 )</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>kelvin</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fahrenheit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rankine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>temperature difference(^d)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Thermal conductivity\(^d\)**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Btu in/(ft(^2) s °F) (International Table Btu)</td>
<td>( = 5.192 \times 10^3 ) W m(^{-1})K(^{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Btu/(ft(^2) s °F) (International Table Btu)</td>
<td>( = 6.231 \times 10^3 ) W m(^{-1})K(^{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 cal(_{IT})/cm(^2) s °C</td>
<td>( = 4.187 \times 10^2 ) W m(^{-1})K(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

**Miscellaneous quantities**

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>litre per mole per centimetre (1 M/cm =)</td>
<td>( 1 ) L( \cdot )mol(^{-1})( \cdot )cm(^{-1})</td>
<td>( = 1.00 \times 10^{-1} ) m(^2)mol</td>
</tr>
<tr>
<td></td>
<td>(molar extinction coefficient or molar absorption coefficient)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G-value, traditionally quoted per 100 eV</td>
<td>( 1 \times 10^{-2} ) eV(^{-1})</td>
<td>( = 6.24 \times 10^{16} ) J(^{-1})</td>
</tr>
<tr>
<td></td>
<td>(radiation yield of a chemical substance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mass per unit area</td>
<td>1 g/cm(^2)</td>
<td>( = 1.00 \times 10^4 ) kg/m(^2)</td>
</tr>
<tr>
<td></td>
<td>(absorber thickness and mean mass range)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^d\) A temperature interval or a Celsius temperature difference can be expressed in degrees Celsius as well as in kelvins.
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PRINCIPLES
FOR ESTABLISHING LIMITS
FOR THE RELEASE
OF RADIOACTIVE MATERIALS
INTO THE ENVIRONMENT

ANNEX 1982
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SAFETY SERIES No. 45

PRINCIPLES
FOR ESTABLISHING LIMITS
FOR THE RELEASE
OF RADIOACTIVE MATERIALS
INTO THE ENVIRONMENT

ANNEX 1982

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1982
FOREWORD

Since the publication of Safety Series No. 45 in 1978 there have been important developments in radiological protection, and the Agency's Board of Governors has approved a revision of Safety Series No. 9, Basic Safety Standards for Radiation Protection, which was jointly sponsored by the International Atomic Energy Agency, the World Health Organization, the International Labour Organization and the OECD/Nuclear Energy Agency. The main stimulus for change came from a number of publications and statements from the International Commission on Radiological Protection which have made some of the concepts and quantities defined in the 1978 text out of date. Rather than attempt a major revision of the text at this time, since further rapid development is expected in the next few years, this Annex has been prepared, as an interim measure, to highlight some of the most important changes. It should be read in conjunction with the original text and appendices as a review of the basic concepts and quantities to be used by national authorities in setting limits for planned releases of radioactive material into the environment. In addition to an eventual major review of Safety Series No. 45, the Agency plans to publish more detailed guidance on how to apply these concepts and quantities in practical situations.

The Annex was compiled during and after an Advisory Group Meeting in September 1981, chaired by Professor B. Lindell. For practical and editorial reasons the original text of Safety Series No. 45 has been left unchanged.
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CONTENTS OF THE ANNEX

CHAPTER A-I. CONCEPTS AND QUANTITIES ....................... 1
Dose quantities ............................................................... 1
Limits and reference levels .............................................. 4
Recommended primary and secondary limits for the public ...... 6

CHAPTER A-II. COMPLIANCE WITH DOSE LIMITS .............. 9
Source upper bounds ...................................................... 10
Models for predicting exposure in critical groups ................. 12

CHAPTER A-III. ASSESSMENT OF COLLECTIVE DOSE
COMMITMENTS .................................................................. 15
Direct assessment ............................................................ 15
Indirect assessment .......................................................... 16

CHAPTER A-IV. OPTIMIZATION OF PROTECTION ............. 17
Assessment of costs ........................................................ 18
Cost of protection .......................................................... 18
Cost of radiation detriment .............................................. 19
Future detriment ............................................................. 20
Constraint of finite resources .......................................... 21

NEW TERMS AND SYMBOLS ........................................... 23
REFERENCES ..................................................................... 27
LIST OF PARTICIPANTS .................................................... 29
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A-I—1. The release of radioactive materials from nuclear power plants, nuclear fuel cycle facilities, and from other installations using radioactive materials for medical, research and industrial applications constitutes a source of radiation exposure to man which should be controlled within the system of dose limitation recommended by the International Commission on Radiological Protection in ICRP Publication 26 [1]:

"(a) no practice shall be adopted unless its introduction produces a positive net benefit;
(b) all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and
(c) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission."

These guiding principles have become known as justification of the practice, optimization of protection, and individual dose limitation; further explanation of these principles can be found in the 1982 edition of the Agency’s Basic Safety Standards for Radiation Protection [2].

DOSE QUANTITIES

A-I—2. In ICRP Publication 26 and a subsequent statement by the Commission in 1978 [3], the quantity effective dose equivalent has been defined to ensure that, for a given level of protection, the risk be equal either when the whole body is irradiated uniformly or when there is only
partial or non-uniform irradiation. The *effective dose equivalent* is defined as

$$H_E = \sum_{T} w_T H_T$$

where $H_T$ is the mean dose equivalent in tissue $T$ and $w_T$ is a weighting factor representing the proportion of the detriment from stochastic effects resulting from tissue $T$ to the total detriment from stochastic effects when the body is irradiated uniformly. The values of $w_T$ are specified by ICRP [1] and are:

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$w_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.25</td>
</tr>
<tr>
<td>Breast</td>
<td>0.15</td>
</tr>
<tr>
<td>Red bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
</tr>
<tr>
<td>Bone surfaces</td>
<td>0.03</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.30</td>
</tr>
</tbody>
</table>

A value of $w_T$ of 0.06 is applicable to each of the five organs or tissues of the remainder receiving the highest dose equivalents, and the exposure of all other remaining tissues may be neglected. The hands, forearms, feet, ankles, skin and the lens of the eye should not be included among the remaining organs. However, to assess the small risk of fatal cancer resulting from exposure of the skin, a value of $w_T$ for skin has been recommended by the ICRP [3] at 0.01. (The stomach, small intestine, upper large intestine and lower large intestine should be treated as four separate organs when assessing the dose to the gastrointestinal tract.)

2
A-I—3. The effective dose equivalent quantities provide a measure of the risk from fatal cancers and hereditary defects in the first two generations. Such quantities do not, however, account for other stochastic health effects such as non-fatal cancers and severe deleterious effects following the first two generations, which may be important for assigning a cost to radiation detriment. Given certain judgements on the relative severity of fatal and non-fatal cancers, it can be shown that, in most cases, effective dose equivalent quantities provide a good measure of health detriment. This will usually be the case for routine low-level releases of mixtures of radionuclides into the environment. For certain radionuclides irradiating the skin, gonads or thyroid, however, effective dose concepts may be augmented to allow for the risk of non-fatal cancers and hereditary defects after the first two generations [4].

A-I—4. The collective effective dose equivalent, $S_E$, in a population exposed to a given source, is defined as:

$$S_E = \int_{H_E = 0}^{H_E = \infty} H_E P(H_E) \, dH_E$$

where $P(H_E) \, dH_E$ is the number of individuals receiving an effective dose equivalent in the range $H_E$ to $H_E + dH_E$ from the given source. The collective effective dose equivalent can also be defined as the weighted product of effective dose equivalent due to the source and number of individuals in the exposed population. To obtain a measure of the total exposure of the population over a period of time, the quantity collective effective dose equivalent commitment, $S_{E,C}$, is defined as the infinite time integral of the collective effective dose equivalent rate, $\dot{S}_E(t)$, due to a given event, decision, or practice:
\[ S_{E,C} = \int_{t=0}^{t=\infty} \dot{S}_E(t) \, dt \]

**A-I—5.** To assess the total dose equivalent to an individual resulting from an intake of radioactive material, the dose equivalent rate has to be integrated over the future life span of an individual. The **committed effective dose equivalent**, \( H_{E,50} \), resulting from an intake of radioactive material into the body, is the effective dose equivalent that will be accumulated during the 50 years following the intake:

\[ H_{E,50} = \int_{t_0}^{t_0+50\text{ years}} \dot{H}_E(t) \, dt \]

where \( \dot{H}_E(t) \) is the effective dose equivalent rate from the intake and \( t_0 \) is the time of intake. The **committed effective dose equivalent** can be considered as an approximate lifetime effective dose equivalent for workers because 50 years represent the full span of a normal working life. However, for members of the public it may be appropriate to extend the integration time beyond 50 years in order to assess the “lifetime dose” conservatively.

**LIMITS AND REFERENCE LEVELS**

**A-I—6.** A limit is a quantity of effective dose equivalent which should not be exceeded. The primary limits in the Agency’s *Basic Safety Standards* [2] are those recommended by the International
A-I—7. The limits are:

(a) *Primary dose equivalent limits*, as defined by ICRP. These limits apply to individuals or members of a critical group.

(b) *Secondary limits*, required when primary dose equivalent limits cannot be applied directly. In case of external exposure, secondary limits can be expressed in terms of the dose equivalent index. For internal exposure, secondary limits are derived from the Annual Limits on Intake (ALI) given by ICRP for workers [5]. For members of the public the secondary limits are discussed in detail in Section A-I—10 of this Annex.

(c) *Derived limits*, designed to provide direct comparisons with measured quantities other than dose equivalents, such as ambient concentrations of radionuclides in the environment. These are defined by using suitable models, relating the concentrations to doses received by members of a critical group. Derived limits are related to the primary limits by a defined model such that if the derived limits are observed, it is likely that the primary limits would also be observed [2].

(d) *Authorized limits*, defined by a competent authority. These are usually limits on the amount of radioactive material discharged as effluent, and are set to ensure that individuals or members of a critical group do not receive doses above the primary or secondary limits. Models relating the level of discharge to individual doses can be used for this purpose. Limits set by an operator on the basis of similar considerations are normally called operational limits.

A-I—8. Reference levels are not limits. They are, instead, values of quantities used to determine particular courses of action, such as
recording, investigation or intervention. These levels are defined by practical radiological protection considerations and, in the case of intervention levels, will be specified in advance by the competent authority for use in abnormal or unplanned events. A reference level can be established for any quantity used in radiological protection, whether or not a limit exists for that particular quantity.

RECOMMENDED PRIMARY AND SECONDARY LIMITS FOR THE PUBLIC

A-I—9. The annual effective dose equivalent limit for members of the public in a critical group is 5 mSv (0.5 rem), while the annual dose equivalent limit for individual organs or tissues is 50 mSv (5 rem). When members of the public could be exposed at or near the annual effective dose equivalent limit for prolonged periods of time (i.e. many years), it would be prudent to take measures to restrict their lifetime effective dose equivalent to levels below an annual average of 1 mSv (0.1 rem) [1, 2].

A-I—10. Secondary limits for the internal exposure of members of the public may be derived from the annual limits on intake (ALIs) for workers, given in the Agency’s Basic Safety Standards [2]. The following fractions of ALIs for particular radionuclides have been suggested:

One tenth or one fiftieth of the relevant occupational ALI value, if the exposure involves a critical group of adults only, to correspond to the dose limit of 5 mSv and the annual average value of 1 mSv, respectively.

One hundredth of the relevant occupational ALI value, if the exposure involves a critical group of infants or children, to take into account the effect of the organ sizes and metabolic characteristics.
The latter factor of one hundred could be used if specific ALIs are not available for members of the public, but it should be recognized that this would be a very cautious assumption in many circumstances. In an optimization, more realistic values are required and such cautious ALI values for members of the public should not be used.

In cases of combined exposure to external and internal sources or to internal exposure from different radionuclides, the sum of achieved fractions of the appropriate limits (secondary or primary) shall not exceed unity.
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A-II—1. During normal operations, doses above prescribed limits are unacceptable. In the case of radioactive effluent control, the relevant dose limits are those for individual members of the public, in practice applying to the average effective dose equivalent in the "critical group" \[1, 2\]. The dose limits are not intended for use in design or in operation planning because doses below the limits are not automatically acceptable. Instead, a process of optimization should be used to ensure that exposures are kept as low as reasonably achievable. Furthermore, the dose limit applies to the combined exposure from many practices, and it therefore cannot be used as an upper bound for the optimization of a single practice. Exposures at the limit from one practice would preclude other exposures of the same critical group, even if such other exposures are due to justified sources with optimized protection.

A-II—2. When optimizing radioactive effluent control under the constraint of the dose limits, further restrictions are needed. The practice itself could be continuous, with a succession of annual discharges, each generating a dose rate in the critical group which is a function of the time elapsed since the discharge. The dose rate resulting from the combined effect of all such annual discharges will increase, eventually reaching a steady state or a maximum value if the practice is discontinued in the future. Other discharge practices may also expose the critical group, and this contribution may build up to a maximum value too, if the practices are continuous, and be maintained over a considerable period of time. Optimization of effluent control should therefore be carried out under the constraint of values of individual dose which are smaller than the dose limit, to take account of:

(a) The possible continuing nature of the practice itself;
(b) Regional and global contributions from all other present and foreseen sources; and
(c) The need to reserve some margin for future developments of the practice or other practices.

A-II—3. The considerations listed above require judgements by competent authorities which are not purely technical in nature, particularly those regarding predictions about the future. In practice, an individual dose upper bound can be defined to constrain optimization of a given effluent control, so that individual doses are fractions (usually small) of the dose limits. This can be achieved ensuring that, within a critical group, the following relation applies:

\[
\frac{H_{I,d}}{H_{E,L}} + \sum_i \frac{I_i}{I_{L,i}} \leq z
\]

where \(H_{I,d}\) is the annual deep dose equivalent index, \(H_{E,L}\) is the effective dose equivalent limit, \(I_i\) is the annual intake of nuclide \(i\), \(I_{L,i}\) is the ALI for members of the public for nuclide \(i\), and \(z\) the fraction of the dose limit adopted as upper bound for the source under consideration, known as the source upper bound (SUB).

SOURCE UPPER BOUNDS

A-II—4. A continued practice at a constant rate of effluent discharge may be regarded as a series of events, each generating a per caput effective dose equivalent rate which is a function of the time elapsed since the event. The combined per caput effective dose equivalent rate will increase, eventually reaching a steady-state value. This value can be calculated by integrating the contributions to an arbitrary time \(T\) after the steady state has been reached:
where $\bar{R}$ is the practice rate (units of practice per unit time); $\bar{H}_{E,1}(t)$ is the per caput dose rate per unit practice at a time $t$ after that unit practice; and $H_{E,C,1}$ is the dose equivalent commitment per unit practice. If the population group size remains constant, $N$, then

$$\bar{H}_{E} = \frac{\bar{R}}{N} S_{E,C,1}$$

where $S_{E,C,1}$ is the collective dose equivalent commitment in that group per unit practice.

A-II—5. Expansions of present practices can be taken into account by increasing $\bar{R}/N$ appropriately. In the following discussions local environment will be taken to mean all locations where similar radioactive discharges affect the same critical group. The maximum future annual dose in the critical group, from the expanded practice in the local environment, could be assessed from projections of the per caput practice rate:

$$\bar{H}_{E,\xi} = \left( \frac{\bar{R}}{N} \right) S_{E,C,\xi,1}$$

where $\xi$ indicates local contributions.

A-II—6. Regional and global contributions from other similar sources (e.g. reactor discharges) may also expose the critical group involved in the discharge under control. The regional contribution could be assessed, integrating the contributions from all the present and foreseen sources in the region. As an approximation it can be
assumed that the exposure in the critical groups is equal to the per caput exposure in the region or world-wide. The corresponding per caput effective dose equivalents would be given by:

$$\overline{H}_{E,r}^* = \left( \frac{\dot{R}}{N} \right) S_{E,C,r,1}, \quad \overline{H}_{E,g}^* = \left( \frac{\dot{R}}{N} \right) S_{E,C,g,1}$$

where $\overline{H}_{E,r}^*$ and $\overline{H}_{E,g}^*$ are the steady-state per caput effective dose equivalent rate, regional and global, respectively; $(\dot{R}/N)_r$ is the per caput practice rate in the region; $(\dot{R}/N)_g$ is the global per caput practice rate; $S_{E,C,r,1}$ is the regional collective effective dose equivalent commitment per unit practice, and $S_{E,C,g,1}$ is the global collective effective dose equivalent commitment per unit practice.

**A-II—7.** The requirement of individual dose limitation can be formulated as:

$$\overline{H}_{E,L}^* \leq \overline{H}_{E,r}^* + \overline{H}_{E,g}^* \leq z \overline{H}_{E,L}^*$$

where $z$ is the fraction of the effective dose equivalent limit adopted by the competent authority as the source upper bound on the basis of considerations in Sections A-II—2 and A-II—3 of this Annex.

**MODELS FOR PREDICTING EXPOSURE IN CRITICAL GROUPS**

**A-II—8.** Following the release of radionuclides into the environment, the pathways leading to human exposure can be in series and in parallel. The total transfer factor of a pathway in series is the product of the transfer factors involved; the total transfer factor of several branches in parallel is the sum of the transfer factors of the branches. The annual effective dose equivalent in the critical group, $H_{E}^*$, in steady state is therefore given by the relation:
\( H_E^* = \sum_i q_i \sum_P \prod_S f_{uvi} \)

where

- \( q_i \) is the annual activity released of nuclide \( i \)
- \( \sum_P \) indicates the summation over branches in parallel
- \( \prod_S \) indicates the product over pathways in series
- \( f_{uvi} \) are all the relevant transfer factors for nuclide \( i \), including a factor converting to effective dose equivalent.
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CHAPTER A-III

ASSESSMENT OF COLLECTIVE DOSE COMMITMENTS

DIRECT ASSESSMENT

A-III—1. The general method for direct assessment of collective dose is to divide up the exposed population into subgroups such that the exposure is reasonably homogeneous, calculate the average dose rate in the subgroup and the number of people in the subgroup as a function of time, and then sum over all subgroups. The selection of subgroup populations will depend on the characteristics of the release and the environment into which the release is made. It will also depend on the type of models adopted to calculate the behaviour of radionuclides after release and the pathways to man. When the direct method is used for the assessment of $S_{E,C}$, the components should be retained and presented together with the single result. In many assessments the most convenient population subgroups are the local, regional and global populations.

A-III—2. The local population will normally include the critical group and be geographically close to the discharge point, or include consumers of a locally harvested foodstuff who may not live in the vicinity. This local population will contain people who, for reasons of their habits or activities, will receive doses substantially greater than the average of the total population. The habits and other factors leading to exposure in the regional population may be assessed in less detail than that used for the local population, but with more precision than the very general assumptions made for the global population. The “region” may be defined geographically, by the habits of the group, by limitations of analytical models in predicting dispersion, or by any suitable parameter. The global population is taken as the population of the world and the estimation of the collective dose is normally based on relatively simple models. Although this portion of the collective dose tends to
consist of very small individual doses, since there are so many individuals involved it can be the largest contributor to the total collective dose.

INDIRECT ASSESSMENT

A-III—3. An approximate assessment of the collective dose equivalent commitment can be achieved when the total intake of contaminated foodstuff is known. The quantity which can be used in assessing intakes to give collective doses is the committed effective dose per unit intake, $H_{E,50}$, so that $S_{E,C}$ in this case is given by

$$S_{E,C} = H_{E,50} I$$

where $I$ is the total intake and

$$I = \int_0^\alpha \dot{I}, \, dt$$

where $\dot{I}$ is the collective intake rate evaluated by either measurement or mathematical modelling.
A-IV—1. Optimization of protection is the second part of the
system of dose limitation recommended by the International Commission
on Radiological Protection, requiring that all exposures be kept as low
as reasonably achievable, economic and social factors being taken into
account. Techniques for optimizing levels of protection have been
discussed in the Agency’s Basic Safety Standards for Radiation Protection
[2] and in a number of other documents [6—14]. The method proposed
by ICRP is a form of cost-benefit analysis, intended to define levels of
protection such that any further reductions in exposure are unwarranted
[1]. This is achieved by assessing the costs of protection and the benefits
of reductions in exposure, and identifying the protection level which
minimizes the total costs, i.e. the sum of the cost of protection X and
the cost of radiation detriment Y. A schematic diagram of this procedure
is given on page 48 of the main text. The cost of radiation detriment Y
is often assumed to be proportional to the collective effective dose
equivalent commitment $S_E$ of the practice. If other factors, such as
public risk perception, are to be included in the cost of radiation detri-
ment, then Y could also be a function of individual doses $H_i$ in various
exposed groups $N_i$ so that, in general,

$$ Y = \alpha S_E + \beta \sum N_i f(H_i) $$

where $\alpha$, $\beta$ are factors for converting levels of dose into monetary terms.
Thus, in order to apply the optimization requirement, the cost of
detriment from radiation exposure needs to be quantified in monetary
terms, which in turn requires careful judgement.
A-IV—2. When considering the optimization of radiation protection as it affects the release of radioactive material, a number of options will usually be available for the control of exposure. For example, liquid and gaseous effluents could be made to pass through either hold-up facilities, which would reduce public exposure by allowing short-lived radionuclides to decay, or purification facilities, which would remove radionuclides from the effluent stream. Both options will, however, incur costs in terms of capital equipment and may increase the exposure of workers on the site. There may also be subsequent waste-management costs, particularly for purification systems, such as the disposal of spent resins. The technique of optimization provides a means of identifying and balancing costs in a systematic way, thus providing an explicit and informed input into resource allocation decisions in radiological protection.

COST OF PROTECTION

A-IV—3. The estimation of costs of protection is, in principle, a straightforward procedure, although considerable complexities may arise when detailed costs of plant, materials, energy and labour have to be considered. Typically the costs of radiological protection will involve an initial capital investment with operating and maintenance costs over subsequent years. In order to compare alternative protection options with different capital and operating costs, present worth or annualization methods are commonly used to normalize costs [15, 16]. These methods will give the same ranking of alternative projects, in order of increasing costs. Other methods are available, and accounting practices will vary from country to country; in general the complexity of the method employed in any instance should reflect the level of investment being considered.
A-IV—4. The concept of radiation detriment has been defined by ICRP as the expectation of harm incurred by exposure to radiation, taking into account not only the probability of deleterious effects but also their severity [1]. For most practices giving rise to releases of radioactive materials into the environment, only the deleterious effects on health need be considered because other effects, such as restrictions on access to land or consumption of food, will not occur at normal levels of release. Assigning a cost to radiation detriment is not a matter of science or radiobiology. A judgement is required by competent authorities on the cost of deleterious effects of radiation exposure. In making such a judgement it may be necessary to consider many factors, including what society is willing to pay for risk reductions and the direct costs of premature death, for example loss of output and medical costs. Such considerations are not peculiar to radiological protection; in principle, similar valuations are required in all areas of health and safety, and methods have been developed by those concerned with the allocation of resources in these areas [6, 17–19].

A-IV—5. Radiological impact studies often include the assessment of individual and collective doses, and sometimes also the subsequent estimation of numbers of statistical health effects, both fatal and non-fatal. One method of assigning a cost to radiation detriment is to apply cost conversion factors to measures of dose. For example, it is possible to convert collective doses into costs by using a factor in monetary units per man·Sv. In assigning values for such factors the competent authorities may need to take into account some of the considerations mentioned in Section A-IV—4 of this Annex. Because of this, there are likely to be variations in national practices reflecting different attitudes, needs and constraints. The optimization should nevertheless provide an input to decision-making which should explicitly state the judgements incorporated in the analysis.
A-IV—6. When assessing investments in radiological protection to reduce levels of public exposure from releases of radioactive materials into the environment, an important factor to consider is the influence of such investments on the dose distribution. If a reduction in public exposure leads to an increase in occupational exposure, then this should be clearly indicated as an increased cost of detriment. To do this, levels of occupational exposure need to be converted into monetary terms and, as in the case of public exposure, this will require judgements on the part of national authorities. The conversion factors used in assigning costs to levels of exposure to the public and the worker need not necessarily be the same. In addition, attention should be paid to transfrontier exposures produced by globally dispersed radionuclides and to ensuring reasonable allocation of resources for reducing exposures both national and international. This has been discussed in Chapter A-II of the present Annex.

FUTURE DETRIMENT

A-IV—7. Given the long half-lives of various radionuclides, it is possible to calculate potential radiation detriment in populations that might exist thousands of years hence. Some standard accounting procedures would automatically assign less present worth to future costs, whether they be costs of protection or detriment. This is a matter for careful judgement by national authorities, who must decide whether it is reasonable to attach less weight to doses far in the future than to doses predicted for the near future. Discount rates are a commonly used mechanism for reflecting such judgements; a rate of 0% would attach equal weight to doses occurring over all periods of time, while positive discount rates correspond roughly to including doses up to a truncation time equal to the inverse of the discount rate [12].
A-IV—8. Ideally, the factors chosen by national authorities to convert levels of dose into monetary terms should reflect society's willingness and ability to pay for marginal reductions in the mortality rate. In theory there would therefore be no special constraint on limited resources, but in practice the allocation of resources to health and safety is not simply related to the mortality rate from various practices. Consequently there will often be constraints on the level of resources to be devoted to radiological protection, and in such cases cost-effectiveness analysis can be used to compare the protection options. This analysis will define either the maximum reduction in exposure for a fixed cost or the cheapest way of achieving a predetermined reduction in exposure [12, 16]. Although such an analysis might be required when there are certain overriding economic or social considerations, cost-effectiveness analysis is not optimization as recommended by ICRP, a point not made sufficiently clear in the main text of this document. Cost-effectiveness analysis can nevertheless play a role in radiological protection when evaluation of the cost of radiation detriment has either not been made or is not appropriate [14].
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This Annex contains a number of new terms and symbols, which are listed below. Inevitably there are some small differences between the symbols used here and those used in the main text of this document, but the following list reflects what has become common usage in radiological protection. For a more exhaustive explanation of some of the terms and symbols, the interested reader should refer to the Agency’s revised *Basic Safety Standards for Radiation Protection*, Safety Series No. 9 [2].

- **ALI** Annual limit of intake (see the Agency’s revised Safety Series No. 9, *Basic Safety Standards for Radiation Protection*, for detailed description).
- **SUB** Source upper bound, described in Chapter II of this Annex.
- **\( H_E \)** Effective dose equivalent.
- **\( \dot{H}_E \)** Effective dose equivalent rate.
- **\( H_{E,50} \)** Committed effective dose equivalent.
- **\( H_{E,L} \)** Effective dose equivalent limit.
- **\( \dot{H}_{E,1} \)** Per caput effective dose equivalent rate per unit practice at time (t) after that unit practice.
- **\( H_{E,C,1} \)** Per caput effective dose equivalent commitment per unit practice.
- **\( \bar{H}_{E}^* \)** Future maximum or equilibrium combined per caput effective dose equivalent rate resulting from a continued practice at constant rate of effluent discharge.
- **\( \bar{H}_{E,L}^* \)** Future maximum or equilibrium combined per caput effective dose equivalent rate in the local environment.
- **\( \bar{H}_{E,r}^* \)** Future maximum or equilibrium combined per caput effective dose equivalent rate in the regional population.
- **\( \bar{H}_{E,g}^* \)** Future maximum or equilibrium combined per caput effective dose equivalent rate in the global population.
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\[ H_{i,d} \] Annual deep dose equivalent index.
\[ H_{i,s} \] Annual shallow dose equivalent index.
\[ H_T \] Mean dose equivalent in an organ or tissue T.
\[ w_T \] A weighting factor representing the proportion of the
detriment from stochastic effects resulting from tissue T to
the total detriment from stochastic effects when the body is
irradiated uniformly.
\[ I \] Total intake by a population.
\[ I_i \] Annual intake of nuclide i.
\[ I_{L,i} \] Annual limit of intake for nuclide i.
\[ q_i \] Annual release rate of nuclide i.
\[ \dot{R} \] Practice rate per unit time.
\[ S_E \] Collective effective dose equivalent.
\[ \dot{S}_E \] Collective effective dose equivalent rate.
\[ S_{E,C} \] Collective effective dose equivalent commitment.
\[ S_{E,C,1} \] Collective effective dose equivalent commitment per unit
practice.
\[ S_{E,C,\ell,1} \] Collective effective dose equivalent commitment in the local
population per unit practice.
\[ S_{E,C,r,1} \] Collective effective dose equivalent commitment in the
regional population per unit practice.
\[ S_{E,C,g,1} \] Collective effective dose equivalent commitment in the global
population per unit practice.
\[ f_{uv} \] Transfer factor relating the time integral of the concentration
of nuclide i in compartment u to compartment v.

\[ \sum_{P} \] Summation over pathway branches in parallel.

\[ \prod_{S} \] Summation over pathway branches in series.
\( \alpha \)  Factor for converting collective effective dose equivalent commitment into monetary terms for the purposes of optimization.

\( \beta \)  Factor for converting collective effective dose equivalent commitment in population subgroups to monetary terms for the purposes of optimization.

\( z \)  Fraction of the dose limit chosen by competent authorities for defining source upper bounds.
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