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PRINCIPLES FOR LIMITING RELEASES OF RADIOACTIVE EFFLUENTS INTO THE ENVIRONMENT
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PRINCIPLES
FOR LIMITING RELEASES
OF RADIOACTIVE EFFLUENTS
INTO THE ENVIRONMENT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1986
THIS SAFETY GUIDE IS ALSO PUBLISHED IN FRENCH, RUSSIAN AND SPANISH

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FOREWORD

This publication is concerned with the subject of limiting releases of radioactive effluents during normal, controlled operations of nuclear installations. It does not deal with releases from accidents where it is only possible to limit exposures by intervention. In practice, a choice must be made between releasing radioactive materials directly from an installation, storing them, treating and disposing of them by some other means, or some combination of these. Many issues are involved in such choices, not all of which are covered in detail in this publication. The appropriate protection principles in such cases will be described in future publications of the International Atomic Energy Agency.

In 1978 the Agency published guidance on the concepts and principles for use by the competent authorities in setting limits for planned releases of radioactive material into the environment (Safety Series No. 45). It was envisaged that a series of complementary documents would be prepared on the application of these principles in various practical situations.

In 1982 the Agency's Board of Governors approved a revision of the Basic Safety Standards for Radiation Protection (Safety Series No. 9) that had been jointly sponsored by the Agency, the International Labour Organisation, the Nuclear Energy Agency of the OECD and the World Health Organization. These Standards were based on the latest recommendations of the International Commission on Radiological Protection (ICRP), which were issued in 1977 (ICRP Publication No. 26).

Since further rapid development in radiation protection policy was anticipated within the next few years, no major revision of Safety Series No. 45 was attempted with the revision of the Basic Safety Standards. Instead, an Annex was prepared to highlight some of the most important developments. This Annex was published in 1982.

Since then, further statements have been issued by the ICRP, clarifying and expanding the 1977 recommendations. Of particular relevance are ICRP Publication No. 37 on cost–benefit analysis in the optimization of radiation protection (1983), a statement from the 1983 ICRP Washington meeting on annual limits of intake for members of the general public (Annals of the ICRP 14 1 (1984)), and a statement from the 1985 ICRP Paris meeting on the dose limits for members of the general public (Annals of the ICRP 15 3 (1985)).

It has therefore now become appropriate to produce this publication as a complete revision of Safety Series No. 45 and its Annex. The Agency is planning a number of complementary publications on the practical application of the basic principles.
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1. CONCEPTS AND QUANTITIES

1.1. Basic principles

1.1.1. Radiation protection is concerned with the protection of man, while still allowing justified activities from which radiation exposure results. The basic objectives of radiation protection are to prevent such detrimental effects as tissue or organ failure, and to limit the probability of induction of cancer and hereditary effects to levels deemed to be acceptable. A system of radiation protection considered adequate to protect man as an individual is assumed to protect other species as populations although not necessarily as individuals.

1.1.2. The ICRP system of dose limitation [1, 2] provides the guiding principles for this publication. The principles are:

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

1.2. Basic requirements

1.2.1. Radioactive materials released to the environment are sources of radiation exposure to man. Such releases may occur from nuclear fuel cycle installations, including nuclear power plants, from other establishments or laboratories that use radioactive materials for medical, research or industrial purposes, and from mining operations.

1.2.2. The basic principles of radiation protection determine the requirements for release limitation. Justification of a practice refers to the introduction of the practice as whole (a given application of radionuclides, electric energy production by nuclear means, etc.) and not to individual parts of the practice such as the management of radioactive effluents. Acceptance of a practice or the choice between practices will depend on many factors, only some of which are associated with radiation protection. For this reason, justification is not discussed further in this publication. The role of radiation protection in justification procedures is to ensure that the detriment from the practice is fully considered in assessing the net benefit of the practice.

1.2.3. The control of releases must be optimized, i.e. the resulting doses must be kept "as low as reasonably achievable, economic and social factors being taken into account". This requirement implies that the detrimental effects of radiation
from a practice should be reduced by protective measures to levels such that further reductions become less important than the additional protective efforts needed. Methods for optimizing release control, which are discussed in Section 4.3, involve the choice between various control options. Of the available options, only those can be considered which result in acceptably low individual doses. The criterion for 'acceptably low' can be derived from the basic dose limit. However, since that limit is individual-related, irrespective of source, account must be taken of the presence of other sources, the continued operation of all these sources in the future, and the eventual introduction of new sources. For this reason a source-related limit, lower than the dose limit and called the source upper bound, must be set by the competent authority as the boundary condition for optimizing. The competent authority is an authority designated or otherwise recognized by a government for specific purposes in connection with radiation protection and for nuclear safety. The source upper bound is further discussed in paragraphs 1.5.3 and 4.2.1 to 4.2.9.

1.2.4. The detrimental effects of radiation are classified as stochastic and non-stochastic. The stochastic effects are characterized by the probability of their occurrence being a function of dose, over a substantial range of doses, while their severity is independent of dose; these are carcinogenic and hereditary effects. For non-stochastic effects the severity depends on the magnitude of the dose and there is a threshold dose below which the effects will not become manifest; tissue destruction is an example.

1.2.5. Owing to the existence of threshold doses, the prevention of non-stochastic effects is achievable in principle by not allowing doses to exceed dose limits selected so as to be sufficiently lower than the threshold.

1.2.6. For stochastic effects the situation is different. For radiation protection purposes it is assumed that there is a proportionality between dose and the probability of a stochastic effect within the range of doses encountered in radiation protection. A consequence of this assumption is that doses are additive in the sense that equal dose increments increase equally the probability of a deleterious effect by a value which is independent of the previously accumulated dose.

1.2.7. Underlying the imposition of dose limits for individuals are the ideas concerning risk from radiation exposure. Optimization entails considering the detrimental effects from all radiation exposures associated with a source. The concepts of individual risk and of detriment in population are discussed in the next two sections.

1.3. Risk and quantities related to risk

1.3.1. The word 'risk' is used in this context to mean the probability that a given individual will incur a severe stochastic deleterious effect as the result of a radiation dose.
1.3.2. Under the assumption of proportionality (paragraph 1.2.6) the risk to an individual is proportional to the effective dose equivalent of that individual. The effective dose equivalent is based on the concept that, at a given level of protection, the risk should be equal whether the whole body is irradiated uniformly or whether there is non-uniform or partial irradiation. The ICRP has established the appropriate weighting factors, $w_T$, for particular tissues, $T$ [1]. The effective dose equivalent, $H_E$, is defined as

$$H_E = \sum_T w_T H_T$$

where $H_T$ is the mean dose equivalent in tissue $T$. In this report, except when specifically indicated, the term 'dose' and the notation 'H' mean effective dose equivalent and $H_E$ respectively.

1.3.3. The ICRP has introduced the concept of committed dose, which is defined as the sum of doses that would be received by an individual over the 50-year period following the intake of a radioactive substance. This concept is needed in order to implement the current basis for radiation protection, which is to limit the lifetime risk committed in a year, rather than the dose delivered in a year. The period of 50 years is chosen by analogy to the former practice for occupational exposure, in which the objective was to assure that, for continued constant annual intakes, the dose would not exceed the annual limit at the end of a 50-year working lifetime. The committed dose is a conservative measure of risk in comparison with the risk associated with an equal dose from external exposure, because of the delay in delivery of dose and the fact that severe stochastic effects are expressed only some years after the dose. Thus, even though doses to a member of the general public may occur for more than 50 years after an intake, the committed dose represents an adequately conservative measure of the average risk committed to a member of the public by an intake [3]. For this reason, dose limitation for intake of radioactive materials by members of the public is based on the committed dose.

1.3.4. The quantity that reflects the risk committed in any one year is the sum of the external dose received in that year and the committed dose from intakes in that same year. The term 'annual dose' in this report includes both quantities.

1.3.5. If a practice continues over a long period, long-lived radionuclides released to the environment cause exposures which initially increase with time. Since one requirement for release control is to keep the annual dose to individuals below the appropriate source-related upper bound, it is the maximum annual dose in the future that must be limited. This can be achieved by limiting the (incomplete) dose commitment, $S_T$, to the critical group from an annual release, for each year of operation of the practice. This dose commitment is the time...
integral of the average dose rate \( \dot{H}(t) \) in the group caused by one year of operation:

\[
S_T = \int_0^T \dot{H}(t) \, dt
\]

If the integration period \( r \) is chosen to be equal to the expected length of the practice and if the practice can be assumed to continue at a constant rate, then the dose commitment from one year of practice is equal to the maximum annual dose in the future. This is illustrated in Fig. 1. It is the annual dose commitment rather than the annual dose that should be limited in the case of continued practices that cause doses also in future years because of long-lived radionuclides remaining in the environment.

1.4. Detriment and quantities related to detriment

1.4.1. The probability (\( R \)) of incurring a severe stochastic effect is assumed to be given by

\[
R = rH
\]

where \( H \) is the effective dose equivalent and \( r \) is the proportionality constant. If all individuals in a group of \( N \) receive a dose \( H \), the expectation of the number of severe stochastic effects, \( \bar{n} \), is

\[
\bar{n} = rHN
\]

When several groups \( i \) composed of \( N_i \) individuals receive doses \( H_i \), the expectation \( \bar{n} \) is given by

\[
\bar{n} = r \sum H_i N_i
\]

The sum \( \sum H_i N_i \) is called the collective effective dose equivalent, hereinafter referred to as collective dose, and \( n \) is the radiation health detriment.

1.4.2. When there is a continuous distribution of doses over a population, the defining summation, \( S \), of the collective dose can be expressed as an integral

\[
S = \int_0^\infty HN(H) \, dH
\]
where \( N(H) \, dH \) is the number of individuals incurring a dose in the range \( H \) to \( H + dH \). The collective dose, \( S \), is an extensive quantity so that if there are components of collective dose, \( S_i \), the total collective dose is given by
\[
S = \sum_i S_i.
\]

1.4.3. In some cases, the exposure of the population is delivered at a varying rate over a period. In these cases it is convenient to define a collective dose rate at
time \( t \), \( \hat{S}(t) \), as the weighted product of dose rate due to the source and number of individuals in the population:

\[
\hat{S} = \int \hat{H} N(\hat{H}) \, d\hat{H}
\]

1.4.4. The collective dose commitment, (the total collective dose), \( S_c \), due to a given decision, event or defined amount of practice, is the infinite time integral of the collective effective dose equivalent rate, \( \hat{S}(t) \), caused by that decision, practice or amount of practice:

\[
S_c = \int_0^\infty \hat{S}(t) \, dt
\]

The collective dose commitment is a measure of the total detriment to health (as a first approximation) from the exposures that result from that source. Further discussion of the concept is to be found in Ref. [4].

1.4.5. The radiation health detriment calculated as \( \bar{n} = \gamma S \) neglects the contribution to the detriment of generations after the second, and of non-fatal malignancies, which are not taken into account in the definition of effective dose equivalent. However, some judgements on the relative severity of fatal and non-fatal cancers show that, in most cases, collective dose provides a good measure of detriment [1, 5, 6]. For specific irradiations of the skin, gonads or thyroid the collective dose based on effective dose equivalent may be augmented to allow for the risk of non-fatal cancers and hereditary defects after the first two generations [7].

1.4.6. In addition to the detriment to health from radiation, other detrimental effects may also have to be considered in any general optimizing assessment. The concern, anxiety and discomfort of individuals due to the presence, or hypothetical possibility of radiation exposures may need to be considered.

1.4.7. By definition, collective dose includes all the doses to all the individuals who are exposed as a result of the source under consideration. Hence, it is not permissible a priori to truncate collective dose calculations in space, in time, or at a given level of individual dose. However, for some purposes it is useful to separate out the parts of the total collective dose which are received by particular populations, at particular levels of individual dose, over particular periods, or at different degrees of uncertainty.

1.5. Limits, reference levels and exemptions

1.5.1. A limit is a value (of a quantity) that must not be exceeded. The primary dose limits for individuals, given in the Basic Safety Standards [2], are those
recommended by the ICRP [1]. As the primary limits are limits for the total dose from all artificial sources (exposures of patients excluded) they are not directly applicable to any particular source. Source-related limits (referred to as 'upper bounds') are therefore needed.

1.5.2. Individual-related limits. In practical applications, the individual-related primary dose limits serve only as bases for determining source-related upper bounds. The value recommended by the ICRP for the limit of the annual dose for members of the public is 1 mSv. The ICRP also states that it is permissible to use a subsidiary dose limit of 5 mSv in a year for some years, provided that the average annual effective dose equivalent over a lifetime does not exceed the principal limit of 1 mSv in a year [8]. With this limitation on the effective dose equivalent, the non-stochastic organ dose limit of 50 mSv in a year becomes unnecessary for most organs [3]. Since the dose equivalents in the skin and the lens of the eye are not included in the computation of effective dose equivalent for the individual [9], organ dose limits must still be used for these two tissues. The dose equivalent limit recommended by ICRP for both the skin and the lens of the eye is still 50 mSv in a year for members of the public.

1.5.3. Source-related limits. The primary dose limits are related to individuals, irrespective of the source of the exposure, and apply to the total dose from all sources subject to dose limitation. Therefore, they cannot, in principle, be applied in full to limit the dose contribution to an individual from a particular source if that individual is liable to be exposed to other sources. Instead, a source-specific limit, often called an upper bound, should apply to the dose contribution to individuals from any specific single sources or practice. The upper bound, to be imposed by the competent authority, should be so selected that the envisaged total of sources, present and future, will not cause doses above the primary limits.

1.5.4. Authorized limits are limits of any quantity specified by the competent authority for a given radiation practice or source. In setting authorized limits, the competent authority should consider both the requirements of individual dose limitation and the principle of optimization of protection. It follows that authorized limits will not permit doses exceeding the upper bound and that they will constrain doses to even lower levels if optimization assessments indicate that this would be appropriate.

1.5.5. For practical reasons, authorized limits relating to releases of radioactive materials into the environment are usually expressed as limits of releases over specified periods of time. The methods for choosing such limits are discussed in Section 4.

1.5.6. Reference levels are not limits but values of quantities used to determine particular courses of action, e.g. recording, investigation or intervention. These levels are defined by practical radiation protection considerations. A reference level might be established by the management of an operation for administrative
purposes, for example, to prompt investigations of a deviation from previous release levels. A reference level can be established for any quantity used in radiation protection, whether or not a limit exists for that particular quantity.

1.5.7. Some competent authorities find it appropriate to define and to set reference release rates for short periods rather than authorized limits. Setting the appropriate authorized limit is particularly difficult in new practices where some evolution or re-assessment of optimization may result in higher or lower release rates being acceptable. The reporting of a release rate above the reference value may be made to depend on a number of practical factors — averaging time, likelihood of a continued release at an elevated level — in a more flexible way than with a definite limit.

1.5.8. Exemptions. There is often a proper need to exempt a justifiable practice or source from some particular regulatory concern. Exemption may sometimes be made on the basis of a generic study showing that the total practice or the total number of individual sources do not need any extra protective efforts to assure that individual doses are sufficiently small and that the extra protection would not be worth while when the possible total detriment is considered.

1.5.9. The term 'de minimis' is sometimes used to indicate dose levels or quantities of radioactive material which would cause only risks which are totally negligible. Even though there are undoubtedly levels of risk increments which would not significantly change the overall radiation risk for the exposed individuals, this is not a sufficient basis to say that such exposures would not be of regulatory concern. It is also necessary to know that the collective dose from such practices or such a set of sources is sufficiently small, even though the collective dose may be comprised of small doses to a large number of individuals.

1.5.10. A competent authority may therefore choose to exempt a particular practice or category of sources from defined regulatory requirements because individual and collective doses received from it are both so low that they may reasonably be ignored.

1.5.11. The cost of an optimization analysis itself would be taken into account by the competent authority in determining what level of collective dose might be ignored. A justifiable practice that leads to negligible individual doses might also be exempted if an optimization analysis indicated that extra protective measures would not be warranted by any reduction in collective doses that could be achieved.
2. ASSESSMENT OF INDIVIDUAL DOSE

2.1. Aims and methods

2.1.1. The purpose of this assessment is to determine the quantitative relationships between the activities of radionuclides released from a source and the resulting doses to individuals.

2.1.2. The general method for assessing the doses to individuals from a particular source has three parts:

(a) The radioactive source term is identified, including the amount, composition, and time distribution of releases; the mode of the release (i.e. the location of points of release and the part(s) of the environment into which the release occurs), and other source-related quantities relevant to the behaviour of radioactive material following its release from the source.

(b) The passage of radioactive material from the source through the environment to man is analysed, using a mathematical model of the environmental pathways. The analysis of environmental transport will usually involve several exposure pathways, which can occur either sequentially or in parallel.

(c) The doses are estimated from the exposures to a concentration or quantity of radioactive material or an external radiation field. The models used for these estimations require assumptions on age, sex, and living habits, and account for the transfer and metabolism of radioactive materials in man.

2.1.3. These assessments are required for those individuals most likely to receive the highest doses from the source. For this purpose, the critical group is introduced. The group is intended to be representative of individuals receiving the highest levels of dose from the particular source and is defined so that it is reasonably homogeneous with respect to factors that affect the dose received. The quantity used is the average dose in the group (see Section 2.3).

2.1.4. The relationship between the release of a radioactive nuclide and the resulting dose commitment to individuals can be written as

\[ H_{jkl}^c = f_{jkl} Q_{kl} \]

where

\[ j = \text{population group} \]
\[ k = \text{release mode} \]
\[ l = \text{radionuclide} \]
\[ H_{jkl}^c = \text{dose commitment from the release} \]
\[ Q_{kl} = \text{activity of the released radionuclide} \]
\[ f_{jkl} = \text{(overall) transfer factor}. \]
FIG. 2. Schematic representation of atmospheric pathways (adapted from Ref. [11]).
2.1.5. The transfer factor \( f_{jkl} \) should be assessed for all potential critical groups since the group that is critical with regard to a particular radionuclide \( l \) and release mode \( k \) may not be the critical group for the actual releases of mixtures of radionuclides. This section discusses how the transfer factor \( f_{jkl} \) can be assessed. In Section 4 guidance is given on how the transfer factors are to be used in determining upper bounds for releases.

2.2. Exposure pathway analysis

2.2.1. Radioactive materials released to the environment give rise to radiation doses to man through a variety of pathways. Representations of some of these pathways are shown in Figs 2 and 3 for atmospheric and aquatic discharges, respectively. The type of transport model that should be used depends on whether time-dependent information is required or whether some form of steady state can be assumed. Models for use in the latter case are called concentration factor or steady state models while time-dependent models are referred to as dynamic or systems analysis models. Publications of the ICRP [10] and the IAEA [11, 12] discuss these types of models and their limitations and strengths when applied to a variety of different situations.

2.2.2. In some types of facilities, direct external exposure of the nearby population is possible from on-site sources of radiation. Such direct exposures must be considered in assessing the total dose to a potential critical group.

2.2.3. Effluents from nuclear facilities will have various compositions. The environments into which they are released will have different physical, chemical or biological characteristics. 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 could be important.

2.2.4. In most situations, only a few radionuclides in a few pathways will emerge as much more important than all others. The detailed evaluation of these radionuclides and pathways then becomes the essential task. In some cases the analysis may lead to the identification of a critical pathway, i.e., the dominant environmental pathway through which radioactive materials reach the critical group. In such cases the analysis will be considerably simplified.

2.2.5. The initial dose assessment may have to be based on a conservative relationship between release and dose. The early years of operation should be used to attempt to establish more realistic relationships. During the operational lifetime of the source, a continuing review of release, environmental, and monitoring data may be useful for verifying the appropriateness of the pathway models and parameters used.
FIG. 3. Schematic representation of aquatic and direct exposure pathways (adapted from Ref. [11]).
2.2.6. It is important to use models appropriate to the circumstances of an assessment. That is, great complexity is not warranted when not supported by data related to the particular source term or environmental characteristics. In analyses concerned with establishing upper bounds, the quantitative relationship estimated between release rate and doses to individuals must be sufficiently conservative to encompass reasonable uncertainties.

2.2.7. In all the analyses the uncertainties in the results should be established. The uncertainties may arise as a result of real variation in the characteristics of the environment, as a result of a lack of knowledge of the values of parameters needed in models, or as a result of the inadequacies of models to describe the real world. As far as possible, all these uncertainties should be quantified. In addition, the sensitivity of results to variations in parameters and assumptions should be examined. These sensitivity analyses have the aim of determining how robust the models are and of identifying those parameters and assumptions which have most effect on calculated doses. Thus, in sensitivity analyses it is permissible to vary parameters over a range which is not realistic, simply to examine the behaviour of a model. In uncertainty analyses the aim is quantification of the actual uncertainty in results, so parameters should only be varied over a realistic range (or distribution), and correlations between parameters should be taken into account.

2.3. The critical group

2.3.1. Identification of the individuals that are considered as the critical group for a particular radionuclide and release mode may present some difficulties. The ICRP gives general guidance on the matter [13] and competent authorities provide their own solutions. 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 possible critical groups.

2.3.2. In order that the critical group may be relatively homogeneous with respect to dose, the factors which affect the doses received must be identified. The major factors are the location, physiologic and metabolic characteristics, and age, as well as the dietary and other habits of the potentially exposed group.

2.3.3. 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. The group may require further subdivision by age, sex, or individuals subject to additional exposure by way of other routes.

2.3.4. The nature of the critical group is liable to change with time, owing to future variations in the use of the environment to which releases are made and in the
location and habits of potentially exposed populations. It is desirable to make allowances at the outset for these variations when defining the critical group. This may be done by selecting parameters based on maximizing assumptions, e.g. based on food production occurring closer to the point of release than has been found really to occur. If this is not done it is particularly important to keep critical groups under review and to amend the evaluation in the light of any changes.

2.4. Calculation of dose

2.4.1. The environmental modelling discussed in Section 2.2 relates the release rate of any given radionuclide from a particular release point to a concentration in an environmental material to which an individual may be directly exposed. Calculation of the dose from such an exposure is needed.

2.4.2. The procedure for calculating such doses follows two alternative procedures according to the nature of the pathway. This is the final stage of the processes depicted in Figs 2 and 3. For external exposure pathways, the dose to individuals from concentrations of radionuclides in air, water, or on the ground is obtained by applying the appropriate dosimetric models and taking into account shielding effects, annual rate of occupancy, and any other factors characterizing the critical group. For internal exposures, inhalation rates, absorption rates, or ingestion, rates of food and water must be estimated and the relation between intake and dose must be established by means of metabolic models. The ICRP has defined models and parameters which are appropriate for the calculations of doses to adult, occupationally exposed persons [14, 15]. These models and parameters can be used to calculate doses to critical groups if:

(a) the physico-chemical form in which the radionuclide is present in environmental materials is metabolized in the same way as the form encountered in the workplace; and

(b) the critical group consists of adults.

In all other cases, the preferred approach is to use models and parameters which have been specifically defined for the age group, and physico-chemical forms of radionuclides, in question. If this information is not available, the dose per unit intake values for workers given by the ICRP [15] could be used, with a modifying factor to take account of possible differences in radionuclide metabolism with physico-chemical form and the age of the exposed person [2]. It must be recognized that the use of such a modifying factor could lead to the overestimation or underestimation of critical group doses [3].

2.4.3. As mentioned in paragraph 2.1.5, the transfer factors, $f_{jkl}$, should be calculated for all potential critical groups in the case of sources that are a mixture of radionuclides.
2.4.4. In cases of complex combinations of pathways it may be necessary to carry out the analysis over a range of possible critical groups in order to identify the actual critical group $j'$ for a particular radionuclide $i$ and release mode $k$.

2.4.5. The total dose will be made up of a number of components, since account must be taken of exposure from all release modes and radionuclides. However, the critical groups for each radionuclide and release mode may differ. This may be significant in determining release limits, because the applications of controls will often be specific to the various release modes and radionuclides.

2.4.6. Regional and global contributions to doses from other sources that are subject to the dose limitation system must also be estimated. These assessments will usually be made using the type of models discussed in Section 3, rather than through use of the critical group and critical pathway analyses described above. The regional contribution could be assessed, integrating the contributions from all present and foreseen sources in the region. As an approximation, it can be assumed that the dose in any critical group from distant sources is equal to the average doses to individuals in the region and worldwide from such sources (the per caput dose) [4].

3. ASSESSMENT OF COLLECTIVE DOSE

3.1. Aims and methods

3.1.1. As discussed in Section 1, the collective dose commitments from releases of radionuclides may be determined for use in optimizing control of the releases. They may also be used to evaluate the future average dose to the world population from all foreseen releases. It was also noted in Section 1 that the collective dose rate is the weighted product of dose rate and the number of individuals in an exposed population. To a first approximation, the collective dose commitment is the measure of total exposure of the population over time from a given release and an indicator of the total detriment to health from the consequent irradiation.

3.1.2. A general method of assessment of collective dose commitment is to divide the exposed population into subgroups within which the exposures are reasonably homogeneous; calculate, as a function of time, the average dose rate in each subgroup and the number of people in the subgroup and then sum over all subgroups and over time. With this general method the values of the components of the collective dose should be noted and presented together with the total value. In many assessments the values of the components most conveniently chosen are the local, regional and global contributions. For completeness, the occupational collective dose from any control measure associated with the release considered should be included.
3.1.3. In many cases it is possible to use a simpler method for assessing collective dose commitment. In particular, for ingestion pathways the collective dose commitment can be calculated directly from the total intake of contaminated food or water. Total intake may be evaluated by either measurement or mathematical modelling. The disadvantage of this method is that, unless supplemented by information on consumption patterns and rates, it does not provide details of the distribution of collective dose in time, in space, or amongst individuals. These details may be required for use in optimization (see Section 4.3).

3.1.4. The models and parameters used in collective dose calculations should be chosen so as to give realistic estimates of dose, rather than high or maximum values. The modelling used will be similar to those for estimates of individual doses, except that concentrations of radionuclides in environmental compartments extending over regions and globally will need to be estimated. Examples of models used for such estimates and applications are given in Ref. [16].

3.1.5. The local population will normally include the critical group and will be geographically close to the discharge point, or will include consumers of a locally harvested foodstuff who may not live in the vicinity. This local population will contain people who, because 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 spatial detail than that used for the local population. The ‘region’ may be defined geographically, by the habits of the group, by limitations of models in predicting dispersion, or by any suitable parameter. Estimation of the collective dose commitment to the global or worldwide population is normally based on relatively simple models. For example, uniform mixing of a radionuclide in a major part of the environment might be assumed. Although this global portion of the collective dose commitment tends to consist of very small individual doses, it can be the largest contributor to the total collective dose since there are so many individuals involved.

3.1.6. The estimation of collective dose commitments should include all individual doses, regardless of their magnitude and when and where they occur. This implies an extensive calculation but, in practice, the extent of the calculations need only be sufficient for the differences in collective dose commitments associated with various control options to be apparent in an optimization. Thus, components of the collective dose commitments common to all control options are not needed for the comparison.

3.2. Uncertainties

3.2.1. The types of uncertainties in pathway models and parameters which were identified in Section 2 in the context of assessment of individual doses will
also arise in collective dose calculations. In the case of collective doses which are delivered in the far future, there is also the additional uncertainty about the size, location and characteristics of populations. This can lead to large uncertainties in calculated collective dose commitments from long-lived radionuclides.

3.2.2. The uncertainty associated with estimates of the collective dose commitment (and of components of collective dose commitment), will affect the importance which a decision-maker attaches to the results of an optimization study. It is therefore essential to quantify, as far as possible, uncertainties in collective doses, and to indicate the influence that they could have on the selection of the optimum level of control. In particular, if the uncertainties are so large that it is not possible to distinguish between one option and another on the basis of collective dose commitment, this should be stated.

3.2.3. It should also be recognized that there is an inherent uncertainty in estimating numbers of severe stochastic effects when the collective dose commitments involved are small (less than about 100 man\cdot Sv). In such cases the standard deviation of the number of such effects is greater than the expectation value. This should be borne in mind in optimization studies and in deciding on the effort to be devoted to uncertainty analyses of models.

4. SETTING RELEASE LIMITS

4.1. Introduction

4.1.1. Authorized limits for release are set by competent authorities taking many factors into account. If only radiation safety considerations were to be applied, the release limit would be the result of satisfying both the upper bound and the optimization requirements. It would be, therefore, the release corresponding to the result of the optimization procedure carried out under the constraint of the upper bound (i.e. the result of upper-bound-constrained optimization).

4.1.2. Such optimization of the release control systems involves first discarding those control options which do not meet the upper bound requirement. For this reason 'upper bounds for release' must be derived (from the upper bounds of dose) for the relevant environmental situation and the applicable composition of the effluents. The derivation of such upper bounds for release is discussed in Section 4.2.

4.1.3. Control options with releases not exceeding the upper bounds for release are then subject to optimization analysis, by cost–benefit or other methods, and the optimum control option is selected, as discussed in Section 4.3. The release expected from such an optimal option, with due consideration being given to the
fluctuations in release, would be the release limit. The limit should be expressed in a form useful for actual application and for regulatory surveillance. These practical aspects are discussed in Section 4.4.

4.2. Calculation of the upper bound for release

4.2.1. The primary dose limits, which apply to the sum of all controlled exposures of an individual from all sources, cannot be used directly to control the dose to an individual from one particular source. Instead, a lower, source-specific dose limit, the upper bound (UB), applies. This is the boundary condition of any optimization assessment of radiation protection and limits the exposure of the most exposed individuals (the critical group, see Section 2). This section deals with the calculation of the corresponding upper bounds for release.

4.2.2. The derivation of the release upper bound proceeds as follows. The starting quantity is the individual dose limit. The dose upper bound will be less than this by the amount of the contribution of present and foreseen regional and global sources of radionuclides and radiation exposure that are subject to the dose limitation system. A further decrement from the dose limit will possibly be the extent to which a competent authority may reserve some margin for future developments of the practice (source) in question or others. The possible longevity of the practice being considered is relevant here.

4.2.3. The competent authority might set this margin by specifying that the maximum annual dose in the critical groups with regard to a particular practice (e.g. nuclear power production) should not exceed a fraction, F, of the primary dose limit. This maximum annual dose to a critical group, which consists of three components, will be limited by

\[ H_{\text{local}} + H_{\text{regional}} + H_{\text{global}} \leq F \times H_{\text{limit}} \]

where the suffixes refer to the components of the critical group doses and \( H_{\text{limit}} \) is the primary dose limit [17].

4.2.4. Depending on the choice of F and estimates of the contributions expected from regional and global exposures, the competent authority will arrive at the source-specific dose upper bound (\( H_{\text{UB}} \)) that would limit the local contribution from the sources which are under its control. That is,

\[ H_{\text{UB}} = FH_{\text{limit}} - H_{\text{regional}} - H_{\text{global}} \]

Any control of regional and global contributions would have to be exercised through international agreements.

4.2.5. The upper bound for annual release may be derived from the dose upper bound by use of the overall transfer factors (\( f_{jk} \)), estimated as described in
Section 2, where \( j \) denotes population group, \( k \) denotes release mode and \( l \) denotes radionuclide. If the annual dose upper bound is \( H_{UB} \) and the dose commitment to the critical group \( j' \) per unit release of a radionuclide is \( f_{j'kl} \), then, if no other radionuclides are released, the release upper bound, \( R_{kl}^* \), is given by

\[
R_{kl}^* = \frac{H_{UB}}{f_{j'kl}}
\]

4.2.6. Normally the situation is much more complicated since many radionuclides and release modes may be involved each with its own critical group. The dose contribution to each population group due to a release \( R_{kl} \) is given by

\[
H_{jkl} = f_{jkl} R_{kl}
\]

Therefore, if there are several release modes, \( k \), subject to a common release limitation, but still only one radionuclide \( l \), it is necessary to prescribe a set of release upper bounds \( R_{kl}^* \) such that

\[
\sum_k f_{j'kl} R_{kl}^* \leq H_{UB}
\]

where \( H_{UB} \) is the appropriate upper bound and \( j' \) refers to the critical group corresponding to the highest of the \( f_{jkl} \) values.

4.2.7. When the releases of one radionuclide, \( l \), are with release modes that are interdependent, this expression defines one single set of \( R_{kl}^* \) values for the radionuclide \( l \) released. If the releases of radionuclide \( l \) can be varied independently, \( R_{kl}^* \) values are not uniquely determined. It should be noted that the critical group may change when the proportions between the releases are changed, thus necessitating a recalculation of the \( R_{kl}^* \) values using a new set of \( f_{j'kl} \) values.

4.2.8. When a mixture of radionuclides \( l \) contributes significantly to the exposure of the group \( j' \) that is critical for the mixture and release modes specified by \( l \) and \( k \), the \( R_{kl}^* \) values must satisfy the condition

\[
\sum_k \sum_l f_{j'kl} R_{kl}^* \leq H_{UB}
\]

This condition does not uniquely determine the upper bounds for release of individual radionuclides or for the total releases due to any one release mode, but defines sets of \( R_{kl}^* \) values that, together, constitute a release at the upper bound.
4.2.9. Different release modes as well as different radionuclides may involve different critical groups, and the group which is the true critical group for any particular combination of release modes and radionuclides may also be different, depending upon the actual distribution over release modes and radionuclides. Therefore, a limitation based on a realistic critical group may become complicated. Two simplifications are possible. One simplification is to postulate the release modes and radionuclide composition that are most likely, and to identify the critical group for this postulated situation. Release upper bounds \( R_{k^*l} \) can then be calculated. It may be considered unlikely, as long as each \( R_{k^*l} \) is respected, that any deviation from the postulated release characteristics will cause overexposure of any new group that may become critical. The other simplification is to define a hypothetical critical group assumed to have all the characteristics and exposure conditions of the various groups that would be critical for each radionuclide and the most critical exposure mode. If this hypothetical group (which has no correspondence in reality) is denoted by the \( j'' \), the release upper bounds \( R_{k^*l} \) would have to fulfil the condition

\[
\sum_{k} \sum_{l} f_{j''k^*l} R_{k^*l} \leq H_{UB}
\]

This expression does not uniquely determine the upper bounds for release of individual radionuclides or for the total releases by any one release mode, but defines sets of \( R_{k^*l} \) values that, together, constitute a release at the upper bound. The use of the hypothetical critical group in this case will introduce a considerable margin of safety.

4.3. Optimization of release control

4.3.1. General. For routine releases of radioactive materials into the environment, the main types of control options are to provide either storage facilities for gaseous and liquid effluents, so that short-lived radionuclides can decay before release, or treatment facilities which remove radionuclides from the effluent stream for disposal by other means. Within these two broad categories there may be a number of different options available. The various options should be identified and their features examined as far as possible, including capital, operating and maintenance costs, the implications for waste management, and the effect on individual and collective doses for both the public and workers under normal and accident conditions. There may be a number of complex trade-offs between these various features. These include the trade-off between doses resulting from contemporary releases and risks associated with disposal of solid waste, and the
choice between options whose characteristics are known with different degrees of
certainty. These are probably best handled by decision-aiding techniques which take account of all relevant criteria.

4.3.2. The derivation of the release, \( R^* \), which satisfies the upper bound, has been
discussed in Section 4.2. As a result of optimization a new release, \( R' \), is derived.
This optimized release will result in a collective dose less than or equal to that
associated with \( R^* \), and must also satisfy the condition in paragraph 4.2.8

\[
\sum_k \sum_l f_{ij}^l R_{kl}^l \leq H_{UB}
\]

or the similar one in paragraph 4.2.9.

4.3.3. The initial step in optimizing thus is to ensure that the releases anticipated
with control options to be considered meet the requirements of source upper
bounds. Any that cannot would not normally be considered in the optimization
although some reappraisal of the dose estimations may be warranted if it is felt
that the calculations have been unduly conservative. Other applicable constraints
have to be considered at this stage; for example, limits on non-radioactive contaminants. The final part of applying the system of dose limitation is then to
optimize protection by choosing the control option for which radiation
doses are as low as reasonably achievable using the methods described in
paragraphs 4.3.4. to 4.3.19 in order to arrive at the corresponding annual release \( R' \).

4.3.4. Methods. Formal decision-aiding techniques that may be used here include
\textit{cost–benefit analysis} and multi-criteria methods [1, 6].

4.3.5. In cost–benefit analysis, the incremental monetary costs of radiological
protection are directly compared with the detriment reduction resulting from the
additional control measures. The reduction in detriment has to be converted into
monetary terms for the comparison. Comparisons might be made on the basis of
some other quantity; the possibilities of such aggregative methods are discussed
in paragraphs 4.3.16 to 4.3.19. It has been recognized that other decision
aiding techniques can be useful in considering features of control options which
cannot easily be quantified in a common unit, but which may be ranged by other
means. The outcome of a cost–benefit analysis could be one feature or factor
considered in such a ranking analysis. Such methods include \textit{multi-criteria
analysis}, which will be discussed in paragraphs 4.3.16 to 4.3.19.

4.3.6. Irrespective of the method used, if the uncertainties in the estimates of doses
associated with particular control options are such that there are no significant
differences between the estimates, then dose will not be an important factor in
selecting the optimum option.
4.3.7. The objective of using cost–benefit analysis to optimize protection is to identify the level of protection which minimizes the sum of the cost of protection and the cost of radiation detriment \([1, 2, 6]\). The cost of the health detriment is assumed to be proportional to the collective dose. Some competent authorities also consider non-health components of detriment, the costs of which are taken to be a function of individual doses as described, for example, in Ref. \([6]\).

4.3.8. In order to apply cost–benefit analysis to the optimization of protection, the cost of protection and the cost of radiation detriment must both be put in monetary terms. 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 \([18, 19]\). These methods will give the same ranking of alternative projects, in order of increasing costs. Other methods are available, such as crude cost estimation \([20]\). 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. It should also specifically include the costs of management of waste materials produced in the control of routine releases.

4.3.9. Assigning a cost to radiation health detriment requires a judgement by competent authorities on the value of avoiding the 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, the 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 \([7, 21, 22]\). The ICRP \([6]\) considers in detail the issues involved in these valuations.

4.3.10. When radionuclides are dispersed over national boundaries, the advice of the IAEA \([23]\) should be followed in allocating values to components of estimated collective dose commitment.

4.3.11. When radiation exposures from very long-lived nuclides persist into the far future, an assessment of the collective dose commitment is highly speculative. In optimization, however, one deals with differences of collective dose commitments between different control options. The period of interest is therefore only the period in which the alternative control options have different influences on the exposure pattern. This shorter period for the relevant (incomplete) collective dose commitment makes such assessments more reasonable than would appear from the half-lives of the nuclides involved.
4.3.12. Some of the remaining components of collective dose commitment, especially those corresponding to the far future, may still be qualified by substantial uncertainty. To include such components in an optimization analysis where differences in collective dose commitment are estimated may invalidate the results of the analysis.

4.3.13. Problems associated with assigning costs to parts of the collective doses occurring over different periods are frequent, especially when a practice leads to environmental contamination by long-lived radionuclides and, therefore, to exposures in future populations. Implicit in taking the cost of detriment to be proportional to the collective dose commitment is a judgement giving the same weight to present and future detriments. Such weighting is not the usual practice in other types of human judgements which involve the traditional economics technique of discounting.

4.3.14. However, on ethical grounds, it has been argued that discounting may perhaps be properly applied within the period of one generation, but that it should not be applied when a substantial part of the detriment will occur in future generations [24]. Some have also expressed the opinion that it is not valid to discount the cost of future detriment committed from a practice carried out at present, because only the present decision is relevant and the future harm is not avoidable through future decisions.

4.3.15. The outcome of a cost-benefit analysis identifies the level of control at which any further expenditure on additional control is unwarranted. Cost-effectiveness analysis, which is a different kind of analysis, is sometimes used to determine either the maximum reduction in exposure for a fixed cost or the cheapest way of achieving a predetermined reduction in exposure [20, 25]. 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 [6].

4.3.16. Multi-criteria methods. The main limitation of cost-benefit analysis is that it requires explicit valuation of all factors in monetary terms. This tends to restrict the range of factors which may be included in the optimization process. Multi-criteria methods do not necessarily require such explicit valuation and are potentially more flexible decision-aiding techniques because they allow additional factors to be considered. For example, for the radiological impact, equity in time and space, risk perception of the public and accident potential are relevant additional factors. The distributions over time of investments and operating costs can be considered. Other useful inputs may be technical factors such as the flexibility and redundancy of a proposed installation or process, its development status, and the extent of technical support or the research and development effort.

4.3.17. Multi-criteria methods may involve aggregation or ranking. Aggregative methods attempt to combine values for all criteria into a single value in such a
way that options may be compared. For this purpose, it is necessary to construct a measurement scale (called a utility function) so that preferences between different values of a criterion are represented by numbers on a common scale. The preferences will be those of the competent authority and may include those of individuals with responsibility for wider issues of public interest. Account is taken of the relative importance of the various criteria by assigning a weight to each. The total value of each option is obtained by summing the weighted values associated with each option. The best option is the one that has the maximum total value.

4.3.18. In ranking methods, one option is considered better than another if the number of criteria for which it is better is sufficient (a satisfying consensus) and if, for the remaining criteria, the differences are not excessive (no substantial disagreement). These two conditions involve the use of some relative assignment of weight to the criteria. The usefulness of these methods is that, in addition to taking into account many criteria, they provide a reasonable procedure for dealing with some factors in a qualitative way.

4.3.19. A word of caution is necessary regarding these methods for aiding decision-making. The optimality of the selected level of protection, and of the system used to achieve it, depends heavily upon the quality of the judgements and data that went into the analysis. Experience has shown, however, that such methods can lead to reasonable choices although they have not yet been applied extensively in determining release limits.

4.4. Selection of the authorized release limit

4.4.1. The authorized release limit is the limit set by the competent authority. Information on the annual release, $R'$, that corresponds to optimized release control (and which cannot exceed the release upper bound $R^*$) is essential for the selection of the authorized limit. The authority may select the optimized control option and set the release limit close to $R'$ but must never set the limit higher than $R^*$.

4.4.2. The releases associated with the optimized level of control are subject to fluctuations because of operational variations, and are also uncertain, depending on the state of development and experience with the practice and controls. Therefore the authorized limit should allow for these variations and uncertainties.

4.4.3. Early in the assessment it should be determined whether the practice under review can be exempted from continuing regulation. As discussed earlier (Section 1.5), there may be particular practices or sources for which the annual effective dose equivalents to the critical group are such a small fraction of the source upper bound that they could be considered negligible and for which the collective dose commitments are so small that they, too, may be considered to warrant no continuing regulation. What is small enough is a judgement that must
be made by competent authorities. Appropriate criteria are currently evolving. The competent authority may choose to exempt such particular practices or sources from continuing regulation.

4.4.4. Authorized release limits are commonly expressed in terms of releases over some period, usually one year, corresponding to the period over which transfer factors are averaged, and consistent with the assumption of a reasonably constant level of practice for which the optimization of the control system was carried out. When these assumptions are not valid, competent authorities must find other ways of expressing the limits.

4.4.5. Competent authorities may recognize local circumstances by specifying additional limits for shorter periods to ensure that short-term fluctuations in releases and in the characteristics of the environment are unlikely to result in any individual doses above the upper bound.
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REFERENCES


GENERAL REFERENCES


EXPLANATION OF TERMS

(See also general references [i] and [ii].)

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