A. GENERAL CONSIDERATIONS

Introduction

(1) The Commission has summarized its recommended basic system of dose limitation in para. 12 of *ICRP Publication 26*.[29] The system has three components which are necessarily interrelated:

(i) No practice shall be adopted unless its introduction produces a positive net benefit.

(ii) All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account.

(iii) The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

(2) These three components are identified by the Commission by the abbreviated terms:

(i) The justification of the practice.

(ii) The optimization of radiation protection.

(iii) The limits of individual dose equivalent.

(3) This report is concerned primarily with the second of these components of the system of dose limitation, the optimization of radiation protection, and with the rationale and techniques to establish what is reasonably achievable in the control of radiation exposures.

(4) A wide range of techniques is available to optimize radiation protection. Some of these techniques are drawn from operational research, some from economics and some from engineering. The use of a given technique implies, explicitly or implicitly, value judgments about the possible objectives of optimization.

(5) Techniques for use in the optimization of radiation protection include, but are not confined to, the procedures based on cost–benefit analysis and it is these procedures that are discussed in detail in this report. It is important to recognize that other techniques, some quantitative, some more qualitative, may also be used in the optimization of radiation protection.

Fields of Application of Radiation Protection Optimization

(6) Optimization of radiation protection applies to all situations where radiation exposures can be controlled by protection measures. It is an important consideration in the selection and design of protection systems for installations and equipment, and in the performance of operations. Although optimization, as a component of the system of dose limitation, applies strictly to situations where the radiation source is under control, similar considerations can be used for planning some of the protective actions to be taken in case of an accident.

(7) The degree of quantification in the techniques used for radiation protection optimization will vary with the different applications. Designers of installations and protection systems will tend to use more quantitative techniques for deciding the degree of protection (shielding thickness, containment, ventilation rates, etc.) that will meet the optimization requirement. Competent authorities may use stylized quantitative techniques of optimization in deriving

appropriate authorized limits and requirements for given types of installations, radiation sources or practices involving radiation exposures.

(8) Optimization of radiation protection during operations usually, but not necessarily always, tends to be less quantitative. Optimization in this case involves decisions regarding the number and qualifications of personnel, the type of individual protection devices used, the organization of work and the appropriate monitoring required. Quantitative assessments of radiation protection optimization are not suggested for daily operational practice. The persons responsible for radiation protection in daily operations will have to follow simpler rules imposed by the competent authority or the management, on the basis of the optimization principle. In addition, they may be guided by the general ambition of optimizing radiation protection, although in an intuitive rather than quantitative way. This attitude of keeping exposures "as low as is reasonably achievable" is not new in radiation protection and is encouraged by the present recommendations, which stress the fact that it may not be good enough to operate just below the dose limits.

Radiation Protection Optimization as a Decision Analysis

(9) An installation, source or practice involving radiation exposures results in a distribution of radiation doses over a number of people. As specified by the third component of the dose limitation system, sufficient protection is always required to ensure that all individuals involved receive doses that do not exceed the appropriate dose limits.

(10) However, the Commission made the basic assumption for radiation protection purposes that there is proportionality between dose and the probability of a stochastic effect, within the range of doses encountered in radiation work. A consequence of this assumption is that doses are additive in the sense that equal dose increments increase equally the risk by a value which is independent of the previously accumulated dose. A further consequence of the assumption is that, in principle, radiation risks in a given situation can be reduced as much as is desired by increasing the level of radiation protection, thus decreasing the exposure.

(11) Different ways of increasing the level of radiation protection, above that required to meet the dose limits, may result in different changes in the distribution of doses, in addition to involving different costs and different degrees of risk and operational inconveniences not related to radiation. Obviously, if all the factors involved are deemed to change favourably as a result of the adoption of a given increased level of protection, such adoption would be automatically required as a necessary step towards what is reasonably achievable.

(12) This, however, is not the usual situation. In general, higher levels of protection cost more, and different options for increasing protection achieve different dose reductions in groups of exposed individuals, sometimes shifting exposures from one group to another group.

(13) Therefore, the selection of the level of protection that meets the optimization requirement is a decision involving many components, some of which are likely to be in conflict with others. The components of the decision problem include the individual radiation doses involved, the cost and difficulties of the possible protection levels to be selected, the resulting impact on the working procedures and all the other effects that the decision is expected to have.

(14) The decision-making process consists in principle of an evaluation of all alternative options of protection taking account of each of the components listed in para. 13. This evaluation is related to stated or implicit preference criteria. Several methods can be used for this decision-making. Some methods are limited to comparisons between options. For example, *multicriteria methods* compare by pairs the various options taking into account all the criteria, to determine whether one option is better than the other, iterating the process to the final decision.

In these methods, one option is considered better than another if the number of criteria for which it is better is sufficient, and if for the remaining criteria the differences are not excessive. These two conditions involve the use of some relative assignment of weight to the criteria. Multicriteria methods usually allow the preselection of the better options, but do not generally lead to a complete ranking. The value of these methods is that they take account of many criteria and provide a simple procedure for dealing with qualitative aspects.

(15) Other methods, called *aggregative methods*, instead of comparing the different options in pairs, attempt to combine the values of the criteria in each option into a single value, ranking the results for the different options in order to select the best. An inherent requirement of these methods is an adequate quantification of the various criteria. The most widely used aggregative methods are based on utility functions to quantify the different criteria. A utility function is a scale expressing the possible values of one criterion by numbers (called utilities) lying between 0 and 1, assigned in such a way that, if one outcome is preferable to another, the utility of the first is greater than that of the second.

(16) Utility functions are not necessarily linear, and have no other foundation than the preferences of the decision maker regarding a given criterion. The decision is based on the total utility of each option, obtained by combination of the several utilities involved. Account is taken of the relative importance of the various criteria by assigning a weight to each. The best option is the one that maximizes total utility.

(17) An important, but by no means exclusive, method based on utility functions is the special case of *cost–benefit analysis*. This procedure assumes that all the criteria involved can be expressed in monetary terms and that utilities are linearly related to such monetarized criteria. In cost–benefit analysis, the weighting of the different criteria is the monetary value of the unit characterizing the criterion.

(18) A word of caution is necessary regarding these quantitative methods of decision-making. The optimality of the selected level of protection, and of the systems used to achieve it, depends heavily upon the quality of the judgments and data which went into the analysis. It is therefore necessary to evaluate the sensitivity of the solution to variations in some or all of the judgmental inputs and data. Such sensitivity assessment allows the identification of the crucial factors in the decision and helps in making the approach more meaningful, particularly when the problem is complex.

Criteria Involved in Radiation Protection Optimization

(19) In order to quantify the deleterious effects of radiation, the Commission has introduced the concepts of *risk* and *detriment*. The risk associated with a given dose is taken to mean the probability that a given individual will incur a particular effect of radiation as a result of the dose received. The detriment, on the other hand, is defined as the mathematical expectation of the amount of harm in the exposed group of people, taking into account both the probability and the severity of the different possible harmful effects. Harmful effects include the stochastic and non-stochastic effects, (adding up to what is sometimes called the *objective health detriment*), as well as the concern and anxiety of the individuals at risk and any adverse consequence for the comfort of these individuals due to restrictions imposed because of the occurrence of radiation exposures.

(20) At exposure levels below the dose limits, as encountered in normal situations, non-stochastic effects are precluded. Provided that the weighting factors, w_T, used in defining effective dose equivalent adequately reflect the relative detriment of the exposure of each organ

or tissue, and, since the risk of each effect is taken to be proportional to the relevant dose equivalent, it is easy to show that the stochastic component of the detriment is proportional to the collective effective dose equivalent.

(21) Obviously, the objective health detriment would not be proportional to the collective effective dose equivalent when large doses are involved, as occurs in radiotherapy or in radiation accidents. In these cases, the contribution of non-stochastic effects to the objective health detriment would require knowledge of all individual doses involved to assess the objective health detriment.

(22) The concern and anxiety of the individuals exposed to radiation can be the result of an amalgam of both rational and non-rational factors. The decision assessments make use of the rational factors, which would include the level of risk and the attitude (aversion) to risk. Under the assumptions made by the Commission in its recommendations, the level of risk is proportional to the individual effective dose equivalent. The attitude toward risk, on the other hand, cannot be taken to be linear with risk at all risk levels. In fact, the aversion to risk may increase more than linearly with risk at a higher risk level. As a result, the contribution to this component of the detriment from each exposed individual would be a function (not necessarily linear and not necessarily the same for all exposed groups) of his individual effective dose equivalent.

(23) Restrictions affecting the comfort of individuals due to the presence of radiation exposures are usually decided on the basis of individual doses and existing national or managerial regulations. This component of the detriment will also be the result of individual contributions, each a non-linear function of individual dose.

(24) All the components of the detriment could be considered separately in the multicriteria methods of decision-making for radiation protection optimization. In cost–benefit methods a monetary value is assigned to the detriment. Taking into account the discussions in paras. 15, 16 and 17, the objective health detriment (if non-stochastic effects are precluded) can be assigned a monetary value αS, where S is the collective effective dose equivalent due to the installation, source or practice under consideration, and α is the monetary cost assigned by the decision maker to the unit of the collective dose quantity, for example the cost assigned to the man sievert.

(25) The other components of the detriment taken together will depend on individual doses. The contribution from one individual of an exposed group can be expressed as a function of individual dose, $f(H)$, which would depend on risk aversion attitudes and national or managerial regulations. The form of $f(H)$ will not necessarily be the same for all exposed groups and may also change, as do all social attitudes, with time. The cost of these components of the detriment could be assessed as $\beta \sum_j N_j f_j(H_j)$, where H_j is the dose equivalent in the individuals of the group j, N_j is the number of these individuals and β is the monetary cost assigned by the decision maker to a unit of these components of detriment.

(26) The technical sections of this report discussing cost–benefit procedures for the optimization of radiation protection express the cost of the detriment as $Y = \alpha S + \beta \sum_j N_j f_j(H_j)$. In actual application of the cost–benefit methodology, the values assigned to α and β by the decision maker will depend on a value judgment of the relative weight of the different components of the detriment. It should be pointed out that in many situations an expression $Y = \alpha S$ would be a good approximation to the cost of the detriment, even if β is not taken to be negligible. This would be the case if all individual doses are small and if the $f_j(H_j)$ functions decrease steeply with decreasing doses.

(27) Procedures for the optimization of radiation protection require consideration of other factors in addition to radiation detriment. In cost–benefit procedures these factors can be

combined in what is called the cost of protection. Any effort to increase the level of protection implies a cost for society in terms of work, time, materials and even risks.

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

(29) The monetary valuation of the protection cost is based on conventional economic techniques that take account of the actual expenses and their distribution in time. These techniques are discussed in the technical sections of this report and are described in detail in the available literature on accounting procedures.

Conceptual Basis of Cost–Benefit Procedures for Radiation Protection Optimization

(30) The basic notion in the application of cost–benefit techniques to decision-making is very simple: an option is selected if the resulting net benefit exceeds that of the next best alternative and not otherwise. In the case of the introduction of a practice involving radiation exposures, the net benefit to society can be ideally expressed as $B = V - (P + X + Y)$, where B is the net benefit from the introduction of the practice, V is the gross benefit, P is all production costs excluding radiation protection costs, X is the cost of achieving a selected level of radiation protection and Y is the cost of detriment associated with that level of radiation protection.

(31) Searching for a value that meets the optimization requirement involves an interplay of the cost of protection and the cost of the detriment, each being a function of the protection level, such that $X(\omega) + Y(\omega) = \text{minimum}$, where the cost of protection and the cost of the radiation detriment are functions of the level of protection represented by ω (e.g. shielding thickness, ventilation rate, alternative options of protective equipment, etc.). It is obvious that the selection of the optimum pair of values for X and Y would maximize the net benefit from the introduction of the practice, provided that V and P are independent of ω.

(32) It should be pointed out, however, that in some cases a change in the level of protection influences the gross benefit of the practice. In these cases, the process of optimization must take account of these changes to maintain the main objective of maximizing the net benefit. This may be the case, for example, in optimizing the protection of patients.

(33) The procedures for optimization must operate within limiting conditions. One of these limitations stems from the requirement of maintaining all individual doses below the appropriate dose limits. Other limitations may be due to technical conditions which are specific for the situation or to a limited availability of resources.

(34) The technical sections of this report discuss in detail the cost–benefit methodology for radiation protection optimization. However, it should be stressed that optimization of radiation protection, as optimization in technology in general, is basically an intuitive process. The quantitative techniques discussed in this report are a substantial aid to optimization, but they are not in themselves the entire process.

B. TECHNIQUES FOR OPTIMIZATION OF RADIATION PROTECTION USING COST–BENEFIT ANALYSIS

Basic Concepts and Quantities

Detriment

The concept of detriment

(35) The concept of radiation *detriment* is essential for the application of cost–benefit analysis to radiation protection. The Commission introduced the concept in order to identify and, when possible, to quantify all deleterious effects due to exposure to ionizing radiation. It has been developed to provide a single quantity representing the combined impact of deleterious effects resulting from exposures to a given radiation source or practice.[29] Other harmful effects, not necessarily caused by radiation, such as conventional occupational injuries, can be incurred in obtaining the selected level of radiation protection. It is, however, assumed that the value of such harm incurred because of the implementation of protection is not a component of the detriment (see para. 72).

(36) The detriment is conveniently described by an extensive quantity; i.e. a quantity characterizing the whole radiation harm, which is divisible into parts that can be counted and added. Therefore, it should conceptually be possible to define components of the detriment and their addition; e.g. if various sources result individually in given detriments, they will produce the sum of those detriments, when occurring together. As the detriment can be divisible into components, it should be possible to assess each one of them individually. The concept of detriment will be used in this report as a source-related concept referring to the radiation impact upon the exposed population group from a single source under consideration, and not to the impact from all sources on an individual.

(37) *ICRP Publication 26*[29] uses the additivity concept when it provides a definition of detriment. The detriment in an irradiated population group is defined as the expectation of the harm to be incurred, taking into account the frequency of each type of deleterious effect and the severity of the effects. If F_ι is the expected number of effect ι (i.e. the expected frequency of effect ι which is caused by the source), whose severity is measured by factor g_ι, then the detriment, G, is given by:

$$G = \sum_\iota F_\iota g_\iota$$

(38) If the total number of exposed individuals, N, is defined, at a given probability of occurrence, p_ι, the expected frequency of an effect is proportional to N. From the expression of para. 37, the detriment can then be expressed as:

$$G = N \sum_\iota p_\iota g_\iota$$

The above equation represents the formal definition given in *ICRP Publication 26*[29] and demonstrates the additivity requirement for N equally exposed individuals, implying N times the detriment expressed for each individual.

(39) The word *risk*, on the other hand, is used by the Commission[28] to mean the probability that a given individual will incur a deleterious effect as a result of an exposure to radiation. It follows that the concepts of risk and detriment are interrelated. If several effects could result from an irradiation, then the total risk (i.e. the probability of experiencing one or more of the possible effects), R, expressed as a function of the risk, p_ι, of each effect, ι, is

$$R = 1 - \prod_i (1 - p)_i)$$

As the values of p_i are usually small in the dose range of interest in radiation protection, then

$$R \cong \sum_i p_i$$

(40) The detrimental consequences of exposure to radiation could include stochastic and non-stochastic health effects in exposed individuals, serious hereditary effects in subsequent generations and other deleterious effects. Examples of other effects are the possible amenity losses associated with contamination of the environment, sufficient to require restricted access to various areas, and the restriction of consumption of foodstuffs from contaminated areas. Also, anxiety resulting from levels of individual exposure could arise within the labour sector, the public or the authorities, in addition to managerial constraints due to the possibility of exceeding authorized limits.

(41) Because of their nature, the other effects are difficult to quantify in terms of frequency and severity. However, if such effects are clearly identified, they should be taken into account in the assessment of the detriment. As the sum defining the detriment can be divided into components, the detriment can be conceptually expressed as an addition of an *objective health detriment*, plus other detriments. These components of the detriment are discussed in the following paragraphs.

Objective health detriment

(42) Optimization of radiation protection takes place in a region where, with few exceptions (e.g. see para. 182), individual doses are always below the dose limits. Therefore, only the induction of somatic and hereditary stochastic effects of radiation would contribute to the deleterious health consequences, since non-stochastic effects should be prevented. There are other effects (e.g. psychological anxiety) which, although they might be considered as health-related, will be discussed along with other components of the detriment (see paras. 48 *et seq.*), since they have as a common feature the difficulty of quantification.

(43) For stochastic effects, it is assumed that increments of risk are proportional to increments of dose equivalent. Then, p_T, the probability of suffering a stochastic effect from exposure in tissue T, can be taken to be proportional to the average dose equivalent received in that tissue, H_T:

$$p_T = r_T H_T$$

r_T being a risk factor per unit dose equivalent in tissue T. When the above equation is substituted into the equation for detriment (see para. 38), the objective health detriment to one person, $G_{H,1}$, becomes:

$$G_{H,1} = \sum_T r_T H_T g_T$$

where g_T is a factor measuring the severity of a deleterious effect for tissue T.

(44) Several approaches could be attempted to give values to the severity factors. *ICRP Publication 27*[31] analysed the use of the reduction of life expectancy (as related to normal life expectancy) as an index of harm. In the case of occupational exposures, one possible quantification of severity could be the lost working time. For radiation protection purposes, it could be assumed, as a first approximation, that the detriment is dominated by the induction of severe hereditary effects in the first two generations and by fatal malignancies. A severity factor

of unity was assigned to each one of these effects. In this case, the objective health detriment to one person becomes:

$$G_{H,1} = \sum_{T} r_T H_T$$

(45) It is convenient to introduce the total risk for whole body irradiation, R, in the equation, so that the objective health detriment to one person can be expressed as:

$$G_{H,1} = R \sum_{T} \frac{r_T}{R} H_T$$

where the summation is a weighted mean whole body exposure and the fraction r_T/R, which will be represented by a factor, w_T, is the fraction of the whole risk resulting from tissue T when the whole body is uniformly irradiated. The value of R is taken to be 1.65 10^{-2} per sievert (1.25 10^{-2} Sv^{-1} for fatal cancers and 0.4 10^{-2} Sv^{-1} for hereditary effects in the first two generations).[31]

(46) In order to limit the risk of stochastic effects, *ICRP Publication 26*[29] introduced the concept of limitation of the above weighted mean whole body exposure. This concept is based on the principle that, at a given level of radiation protection, the risk should be equal irrespective of whether the whole body is totally or partially irradiated and uniformly or non-uniformly irradiated. This condition is met by requiring that the limitation be applied to a quantity, called *effective dose equivalent*,[30] H_E, defined as:

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

(The recommended values of w_T were given by the Commission.[29, 30]) Therefore, the equation of the objective health detriment to one person can be presented as follows:

$$G_{H,1} = R H_E$$

(47) The assessment of the individual objective health detriment, as presented in the previous paragraph, does not include the hereditary contribution to the detriment to generations subsequent to the second generation and due to non-fatal malignancies, since these effects were not taken into account in the definition of effective dose equivalent. Furthermore, the actual risk per unit effective dose equivalent could depend on sex, age and other factors. The possible influence of those detrimental effects on optimization of radiation protection was reviewed by the Commission and resulted in the following statement:[34]

> "Since the publication of *ICRP Publication 26*, there has been an increased use of the effective dose equivalent not only for comparison with the dose limits but also in assessments of collective dose in optimization procedures. Questions have been raised whether it is then appropriate to use the effective dose equivalent without consideration of the total genetic harm and the non-lethal cancers.
>
> The Commission has reviewed this matter and has reached the following conclusions with regard to the use of the effective dose equivalent in optimization assessments. The addition of the future genetic harm in the case of uniform whole body exposure would add a further risk of 0.4 10^{-2} Sv^{-1} in the case of the public, or rather less in the case of the average worker, to the total assumed risk of 1.65 10^{-2} Sv^{-1}; i.e. it would increase the total detriment by at most 24%. In the less likely case that the gonads would receive the dominating dose, the genetic harm would be twice that implied by the effective dose equivalent alone.

The weight of the additional detriment attributed to non-lethal cancer would depend upon the weight to be attached to a given length of time lost from normal health (during illness prior to cure) relative to an equal period of life lost as a result of death from fatal cancer. If that relative weight (K) is taken to be 0.1 (as in *ICRP Publication 27*), the addition of the detriment due to non lethal cancer and the induction of benign tumours would only increase the total non-genetic detriment by 2% in the case of uniform whole-body exposure. If organs such as thyroid and skin, for which cancers have a low fatality rate, are irradiated alone and K is taken to be as high as 0.5, the total detriment will approach about twice that implied by the use of the effective dose equivalent alone. In most cases of external exposure or exposure to mixtures of radionuclides, however, the use of the effective dose equivalent alone would not significantly underestimate the total detriment."

Other components of the detriment

(48) While the objective detriment to health can be quantified given knowledge of the dose, the quantification of other components of the detriment is usually more difficult. Other effects need to be considered on a case-by-case basis, with particular regard to how they can directly affect the detriment. In many situations, especially when individual exposures are very low, other detriments might reasonably be ignored. However, if the psychological stress that a potential exposure may create is considered as detrimental, other detriments can be relevant, even in cases when exposures do not actually, but might hypothetically, occur.

(49) Formal optimization requires, as a specific constraint, that individuals do not exceed the relevant dose limits. In some cases, however, individual doses approach the dose limits and give rise to the objective health detriment as well as to other detriments. Other potential detrimental effects in these cases might be the perception of risk and the anxiety due to the existence of dose limits. The knowledge that exceeding authorized limits might cause managerial constraints brings along anxiety among the people involved. On the other hand, anxiety from perceived risk can be a detriment difficult to quantify and liable to be related to the objective risk in a complex way. The risk perceived by individuals can be equal to, or greater or less than, the actual risk. A risk-averse attitude is characterized by an increasing avoidance of risk as the levels of risk increase. The converse risk-acceptance attitude would be the opposite, with individuals considering dose increments as increasingly irrelevant as the levels of risk increase. The absolute quantification of such attitudes might not be opposite, but this does not mean that anxiety effects should be ignored.

(50) When individual doses are well below the dose limits, the other effects discussed above are negligible, provided that the potential psychological effects mentioned in para. 48 are ignored. In that case, the objective health detriment can be used as a sole measure of the entire detriment. As individual doses increase, other detriments arising from anxieties might have to be considered in the optimization process by adding a component to the objective health detriment. This component may be related to the mean dose equivalent in the groups of highly exposed people and to the number of individuals in each group (see para. 25).

Collective Dose

The concept of collective dose

(51) The *collective effective dose equivalent*, S_E, in a population exposed to a given source, is defined as:

$$S_E = \int_0^\infty H_E N(H_E)\, dH_E$$

where $N(H_E)$ is the population spectrum in terms of effective dose equivalent from the source, $N(H_E)\,dH_E$ being the number of individuals receiving an effective dose equivalent in the range H_E to $H_E + dH_E$ from the source. Integrals of this type are usually called weighted products, the collective effective dose equivalent being the weighted product of the effective dose equivalent due to the source and the number of individuals in the exposed population. In this report, the term *collective dose*, unless specifically qualified, is taken to mean the collective effective dose equivalent.

Collective dose and objective health detriment

(52) The collective dose is useful as an indicator of the objective health detriment, because the objective health detriment to one person is proportional to the effective dose equivalent (see para. 46). The objective health detriment in an exposed population of N individuals receiving an effective dose equivalent, H_E, will be given by:

$$G_H = NRH_E$$

If a population spectrum in terms of effective dose equivalent from the source can be defined, the objective health detriment becomes:

$$G_H = \int_0^\infty RH_E N(H_E)\,dH_E = RS_E$$

where the basic assumption is that the total risk per unit of effective dose equivalent for whole-body irradiation, R, is constant over the values of H_E for which $N(H_E)$ is not zero.

Collective dose rate and collective dose commitment

(53) In some cases, the exposure of the population is delivered at a varying rate over a period of time. In these cases, it is convenient to define a *collective dose rate*, $\dot{S}_E$, as the weighted product of the effective dose-equivalent rate and the number of individuals in the population:

$$\dot{S}_E = \int_0^\infty \dot{H}_E N(\dot{H}_E)\,d\dot{H}_E$$

The total collective dose rate is obtained by including *all* the individuals, within the population under consideration, receiving a dose rate from the source, and is a function of time.

(54) In order to have a measure of the total exposure of the population over time, the quantity *collective dose commitment* is used. The collective dose commitment, S_E^c, due to a given event, decision or practice, is defined as the infinite time integral of the collective dose rate as a function of time, $\dot{S}_E(t)$, caused by that event, decision or finite practice.

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

The collective dose commitment, therefore, gives the measure of the total objective health detriment from a source or practice.

The incomplete collective dose commitment

(55) Sometimes radiation protection options are assumed to isolate the nuclides (which will eventually expose people) for some definite period of time, after which these nuclides are

assumed to return to the environment and disperse as they would without retention. Then, for a given isolation time, τ, the collective dose actually committed is given by

$$S_E^c = \int_{\tau}^{\infty} \dot{S}_E(t)\,\mathrm{d}t$$

The difference between the collective dose commitments from two alternative radiation protection options A and B, which is a relevant quantity in optimization analysis, as shown in paras. 62 and 63, would then be:

$$\Delta S_E^c = \int_{\tau_A}^{\infty} \dot{S}_E(t)\,\mathrm{d}t - \int_{\tau_B}^{\infty} \dot{S}_E(t)\,\mathrm{d}t = \int_{\tau_A}^{\tau_B} \dot{S}_E(t)\,\mathrm{d}t$$

$$\Delta S_E^c = \int_{0}^{\tau_B} \dot{S}_E(t)\,\mathrm{d}t - \int_{0}^{\tau_A} \dot{S}_E(t)\,\mathrm{d}t$$

The last two types of integrals are called *incomplete collective dose commitment*, S_E^{τ}, in this report.

Collective dose and other components of the detriment

(56) The collective dose, which correlates with the objective health detriment in the range of doses where proportionality between increment of risk and increment of dose can be assumed, is not expected to describe adequately other components of the detriment. Therefore, in the process of assessing the detriment and making decisions, national authorities might, if necessary, require more information than that provided by the collective dose.

(57) A change in the level of radiation protection would not only modify the value of the collective dose but might also alter the distribution of individual doses. Optimization, on the single basis of objective health detriment, and thus of collective doses, can be principally dominated by the larger contribution to collective doses from large groups at low levels of individual dose equivalent. In some particular cases, however, the competent authorities might assign special importance to the other components of the detriment and pay special attention to a relatively highly-exposed small group of local individuals whose doses might be close to the authorized limits. In this case, better radiation protection, in the competent authority's terms, might be achieved by an extra reduction in selected individual doses and the optimum level of protection can be more restrictive than that resulting from the use of the objective health detriment alone. A formulation for the valuation of cost of detriment, which takes both collective and individual doses into account, is presented in paras. 25, 26 and 87.

(58) In the algebraical and numerical examples on the use of cost–benefit analysis for the optimization of radiation protection presented in this report, only the objective health detriment will be considered, this being proportional to the collective dose commitment.

The Use of Cost–Benefit Analysis

General Concepts

(59) The Commission has concluded that the phrase *as low as reasonably achievable* can be interpreted by a process of cost–benefit analysis which establishes optimum levels of radiation protection and, in *ICRP Publication 26*,[29] identified a simple way of performing such analysis. The form of cost–benefit analysis recommended by the Commission involves a balancing of costs in order to establish optimum levels of radiation protection. In terms of the formalism used in *ICRP Publication 26*,[29] the *net* benefit B from the introduction of a practice involving ionizing

radiation is the *gross* benefit minus the *costs* of the practice, including the cost of radiation protection and the cost of the remaining detriment. This can be expressed by the equation:

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

where B is the net benefit of the introduction of a practice;

V is the gross benefit of the introduction of such practice;

P is the basic production cost of the practice, excluding the cost of radiation protection;

X is the cost of achieving a selected level of radiation protection; and

Y is the cost of the detriment resulting from the practice at the selected level of radiation protection.

(60) In the cost–benefit analysis recommended by the Commission, the benefits are taken to include all the benefits accruing to society and not just those received by particular groups or individuals. Costs are considered as comprising the total sum of all negative aspects of an operation, including monetary costs and any damage to human health or to the environment (see para. 16 of *ICRP Publication 26*.[29] The determination of costs and, more particularly, benefits and their expression in common terms, calls for the application of economic theories. However, this report does not attempt to include any of the more complex features, such as the effect of people's individual valuation of benefits. Since in most of the situations under consideration the change in benefit is the result of a change in the magnitude of a detriment rather than in the characteristics of that detriment, this simplification will usually be adequate. The formulation put forward by the Commission provides for the inclusion of such features where they are felt to be necessary. Although quantification of costs and benefits in this context will sometimes present difficulties in practice, the principles are crucial and are recommended by the Commission.

(61) The terms of the general equation presented in para. 59 are not only dependent on the level of radiation protection but also on other variables, such as the level of output of the product of the practice. However, the methods presented in this part will make use of cost–benefit analysis techniques only for optimizing the radiation protection of the practice and not the practice itself. Since radiation protection is usually independent from those other variables, the techniques presented will be limited to the search for optimum levels of radiation protection.

(62) As presented in *ICRP Publication 26*,[29] the optimum level of radiation protection is obtained by maximizing the net benefit of the introduction of the practice. Assuming that the collective dose, S, is the relevant independent variable, the maximum would be attained when

$$\frac{\mathrm{d}V}{\mathrm{d}S} - \left(\frac{\mathrm{d}P}{\mathrm{d}S} + \frac{\mathrm{d}X}{\mathrm{d}S} + \frac{\mathrm{d}Y}{\mathrm{d}S}\right) = 0$$

Considering V and P as constant with S for a given practice, *ICRP Publication 26*[29] indicates that the optimization condition is fulfilled at a value, S_o, such that the increase in the cost of protection per unit collective dose balances the reduction of detriment per unit collective dose; i.e.,

$$\left.\frac{\mathrm{d}X}{\mathrm{d}S}\right|_{S_o} = -\left.\frac{\mathrm{d}Y}{\mathrm{d}S}\right|_{S_o}$$

(63) The above procedure for obtaining the solution of optimization has led to the use of the term *differential cost–benefit analysis* to refer to optimization procedures. The level of exposure defined by this equation is such that a marginal increase in the cost of radiation protection is exactly balanced by a marginal reduction in the cost of detriment. In many cases, costs are not continuous variables and alternative radiation protection options result in finite incremental changes in costs. In these cases, the equation could be approximated by:

$$\left.\frac{\Delta X}{\Delta S}\right|_{S_o} = -\left.\frac{\Delta Y}{\Delta S}\right|_{S_o}$$

where Δ represents incremental changes of the variables. Even when the number of alternatives is finite, all the accessible options have to be taken into account, since omitting to include an intermediate option can sometimes lead to a wrong result.

(64) On the other hand, decision-making procedures based on *cost-effectiveness analyses* are simpler and should not be mistaken for optimization methods based on cost–benefit analysis. They prevent the variables from floating independently and could only be used to determine the most effective protection obtainable from fixed resources or, alternatively, the cheapest protection for a given level of exposure. Cost-effectiveness analyses are carried out when a specific dose reduction is required or when the amount of money available for radiation protection is fixed. In this case, the net benefit, B, will be maximized by either varying X, with Y as a constant, or varying Y, with X as a constant. Therefore, cost-effectiveness analyses can only define either the least costly way of achieving a specified reduction in exposure or the maximum reduction in exposure that can be attained for a fixed cost, but cannot optimize radiation protection under the framework presented in this report. Consequently, these types of analyses are not the ones strictly recommended by the Commission for a formal optimization of radiation protection. However, it should be remarked that cost-effectiveness analyses may allow the *a priori* exclusion of available options by simple procedures. Thus, in some cases, a cost-effectiveness analysis might precede and simplify the formal optimization analysis.

(65) Both the cost of radiation protection, X, and the cost of detriment, Y, vary with the level of protection which, in turn, can be characterized by a representative protection parameter, ω. Examples of protection parameters are: thickness of shielding; ventilation flow rate, and operational features, such as the exposure time. The ultimate objective of optimization is to determine the (optimum) values of these parameters, ω_o. Since ω and S are interrelated, in many cases it is technically convenient to perform the differential cost–benefit analysis using ω, rather than S, as an independent variable.

(66) Optimization of radiation protection can be generally limited to the selection of the best available combination of cost of radiation protection, X, and cost of detriment, Y, by minimizing the sum $(X + Y)$, as a function of ω, and, thus, contributing to maximize the net benefit. As already indicated, this process is carried out under the assumption that—in most practices—V and P are independent of the protection parameter. Specific cases exist, however, where it is recognized that the gross benefit, V, and the production cost, P, are dependent on protection; some of them will be briefly discussed in this report (e.g. see paras. 182, 186 and 198).

(67) The minimization of $(X + Y)$ has to be carried out within several constraints. The analysis should consider the variation of several radiation protection parameters and assess the way in which both X and Y are modified by changes in these parameters. On the other hand, the need to respect the dose limits (or fractions of them assigned by the competent authority as upper bounds for a practice) can restrict the range of values of X and Y. Further restrictions might have to be taken into account; e.g. a limitation in the availability of resources for radiation protection (see para. 69).

(68) Optimization of the level of radiation protection, therefore, can be formally presented by a system of mathematical expressions which must be solved simultaneously, as follows:

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

where U expresses the end result of the optimization procedure and is usually called the *objective function* (meaning that it represents the aim of the operation and not the opposite to a subjective function); it has also been designated as "primary design equation" or "optimization function";

X is the cost of radiation protection;

Y is the cost of the detriment; and,

(ii) $X = X(\omega)$

$Y = Y(\omega)$

or, $\psi[X(\omega), Y(\omega)] = 0$

where the pair of equations $X(\omega)$ and $Y(\omega)$ represent the parametric form of the general function ψ and are defined functions of the radiation protection parameter, ω. It should be noted that ω (and $X(\omega)$ and $Y(\omega)$) might be continuous in some cases, while, in other cases, they can only adopt discrete values. Expressions (ii), which are interrelations between the variables of the objective function, are usually called *constraining functions*. ψ also takes the names "equality constraint" and "subsidiary design equation". These functions generally stem either from the laws of physics or from decisions made regarding the valuation of the detriment. In order to avoid linguistic confusion, it should be mentioned that, although the Commission has indicated that the dose limits should be a constraint to the process of optimization, this limitation cannot be performed by constraining functions, but through constraining inequalities as presented below. In many simple optimization assessments (including complicated cases if computing techniques are used) only the parametric expressions of ψ, e.g. $X(\omega)$ and $Y(\omega)$, are needed. However, if Lagrangian multipliers were used, e.g. for solving complicated interrelated cases (see para. 116), the expressions of ψ must be introduced in the optimization process.

(iii) $H_z(\omega) \leq H_L$

where $H_z(\omega)$ is the individual effective dose equivalent incurred by the individual z at a radiation protection level ω and H_L is the relevant dose limit. There should be as many constraining inequalities (iii) as individuals exposed by the practice. These expressions are usually called *limit equations*.

(69) When the resources available for radiation protection are a limiting factor, a further constraint might have to be considered in practice when performing optimization assessments. The limit equation can take the form of $X \leq X_L$ in simple cases, or $\Sigma_\ell X_\ell \leq X_L$ in cases with several ℓ subsystems, where X_L is the limit resource available for radiation protection purposes. It could also be necessary to consider other types of boundaries. Examples of these are: (i) the limitation of collective dose commitments (e.g. in order to ensure that future individual doses due to present and future practices will not exceed an appropriate limit); and, (ii) physical limits in the range of the protection parameter itself.

(70) A formal and simultaneous solution to the objective function, the constraining functions

and the limit equations might be unnecessary in simple cases. In these cases the optimization procedure could conceptually start at a level of radiation protection sufficient to ensure compliance with the dose limit equations and assume that there are no other types of limitation. The constraining functions could then be substituted into the objective function, thus reducing the optimization assessment to the identification of the minimum in the resulting function (see para. 102 *et seq.*).

Assessment of Costs

(71) A successful implementation of the methods recommended for optimizing radiation protection requires the quantification of two relevant parameters. These are the cost of radiation protection, X, and the cost of detriment, Y. This quantification needs to be carried out in dimensionally coherent terms. Since radiation protection costs are usually available in monetary terms, it is convenient (although not mandatory) to assess detriment costs in the same terms. A monetary currency can, therefore, be used to assess both radiation protection and detriment costs. An ideal, non-inflationary currency, the unit of which is expressed in this report as \$, is used in the discussion on assessments of costs and in the examples presented in this report.

(72) The assessment of the cost of protection can be performed by using conventional, simple, costing techniques. It should be noted however that, in theory, an extra term, representing the value assigned to harm associated with the introduction of the protection technique, should be added to the crude protection cost. Reductions in the levels of exposure require improved radiation protection measures, including materials, energy, manpower and other resources needed for their implementation. This extra amount of effort usually implies an associated harm, not necessarily radiological, as a result of the chain of activities leading to the increase of radiation protection; e.g. the production of necessary raw materials and energy, the fabrication of components for the radiation protection system, and the installation of the system. For instance, a decision could be made to diminish a given radiation field by increasing the shielding wall for the source of radiation. This decision would result in a reduction of the radiation detriment but also in an increase in the amount of shielding material needed. The installation of the additional material (e.g. concrete) might produce potential harm to the people involved in activities needed to produce and install the shielding; e.g. occupational harm for mining and milling cement limestone. As indicated before, the change of the harm associated with radiation protection, as a consequence of actions intended to change the radiation detriment, should be evaluated and taken into account when assessing the associated marginal cost of radiation protection. This is, however, a very difficult challenge, due, among other things, to the absence of comprehensive data based on conventional harmful effects. The optimization methods presented in this report will assume that the conventional harm has already been included in the direct costs of the radiation protection system.

(73) The assessment of the cost of detriment is more complicated. Detriment costs can be controversial and can involve implicit or explicit judgments on values of health (and therefore of life) and in some cases of non-health harm. Since the detriment is an extensive quantity (see paras. 36 *et seq.*), the cost of the detriment, Y, can conceptually be divided into components, which can be treated separately

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

where Y_H is the cost of the objective health component of the detriment; and

Y_1, $Y_2 \ldots$ are the costs of the various other significant components of the detriment.

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

(75) It should be recognized that costing the other components of the detriment is even more controversial. Although in the examples given in this report other components of the detriment are disregarded (see para. 58), paras. 25, 26 and 87 introduce a formulation for the valuation of the cost of other components of the detriment concerning the distribution of individual doses.

(76) Most investment decisions require the analysis of various streams of costs and benefits in time, and, consequently, accounting practices have been devised to aid consistent comparisons between competing projects. Generally, the costs and benefits are normalized at a point, or at points, within a given period of time and this can be helpful as an input to a wide range of decisions. In radiation protection, the reductions in the cost of detriment could show a different distribution in time from that of radiation protection costs and, therefore, the use of such methods should be considered (see para. 101). It should be noted that the choice of accounting methods can influence the results of formal optimization.

Cost of protection

(77) The cost of radiation protection encompasses all the efforts made by society to obtain a desired level of radiation protection and is normally expressed in monetary terms. It results from a combination of the capital costs of the radiation protection system and the subsequent operating costs. The accounting techniques currently used in the country concerned should be used to perform that combination in an appropriate way. Although a full description of available accounting techniques is beyond the scope of this report, a brief review of methods commonly used in investment and cost–benefit analyses, which, in turn, may be used for assessing radiation protection costs, is presented. Three general methods for assessing the costs of radiation protection will be described: (a) crude cost estimates; (b) present worth evaluations; and, (c) capitalized cost approaches or annualized cost estimates.

Crude cost estimates

(78) Crude cost estimates are sometimes used in private-sector investment analyses when a venture is regarded as uncertain.[47] The crude cost of an installation, with an initial capital cost, X_c, and an annual operating cost, X_o, is given by:

$$X = X_c + \dot{X}_o \tau$$

where τ is the lifetime of the plant in years. This cost, or a breakdown of costs for each year, can then be directly compared with the benefits occurring over time τ to establish whether a net benefit is present. This approach is normally supplemented by criteria such as net or average rates of return so that a comparison with alternative investments can be made.[47,57]

(79) Crude cost estimates ignore the time variation of monetary resources and, therefore, will make no distinction between radiation protection systems with high capital costs and low

operating costs, and those with low capital costs and high operating costs. In the examples presented in this report, however, crude cost estimates are used in order to determine the cost of radiation protection. If the variation of the value of money with time has to be taken into account, it might be necessary to use more elaborate costing techniques such as those commonly used by economists and cost–benefit analysts. These involve the reduction of streams of benefits and costs to a single value at a specified point in time or the use of methods of annualization.

Present worth evaluations

(80) In order to take account of time, the technique of discounting is commonly used.[57,67] In the practice of discounting, a discount factor is applied to costs as time progresses. The arguments that surround the use of discounting are complex and the application of this technique to the cost of detriment is discussed in para. 101. At this stage the technique of discounting will only be described in relation to investments in radiation protection systems.

(81) A discount factor, γ_n, to be applied in the n^{th} year of cost, can be defined as follows:[67]

$$\gamma_n = \frac{1}{(1+\gamma)^n}$$

where γ is the discount rate. Future cost is apparently valued less than present cost; so, discounting should be regarded as the inverse of compound investment. If X_F is the future amount that a given present amount, X_P, will accumulate at $\gamma\%$ interest in n years time, then,

$$X_P = \frac{X_F}{(1+\gamma)^n}$$

(82) When operating or maintenance costs can be assumed to be constant throughout the lifetime of the plant, the calculation of present values can be simplified by the use of *annuity* factors.[67] These are the sum of discount factors over time periods and are defined as:

$$a_{n\gamma} = \frac{(1+\gamma)^n - 1}{\gamma(1+\gamma)^n}$$

where $a_{n\gamma}$ is the annuity factor;

γ is the interest or discount rate; and

n is the number of years corresponding to the lifetime of the project.

Annuity factors $a_{n\gamma}$ can be found in standard tables.[57,67]

Capitalized cost approaches or annualized cost estimates

(83) An alternative to present worth calculations is to annualize costs. The capitalized cost approach, which is the standard engineering cost analysis technique, assumes that money is borrowed at a given rate to finance the purchase, installation, and operation of the radiation protection system, and is paid back annually. Instead of reducing benefits occurring over time to a single cost at time zero, annualization spreads initial (and usually large) capital costs over the projected lifetime of the installation so that they can be directly added to the annual operating and maintenance costs. This method has been recommended[53] as an input into cost–benefit analysis. The rationale for annualizing costs is pragmatic; normally money has to be borrowed to finance a project and then paid off (amortized) over the lifetime of the project as a series of annual payments.

(84) The annual payments from annualized cost estimates can be calculated using a capital recovery factor,[53,57] $C_{n\gamma}$, defined as the inverse of the annuity factor

$$C_{n\gamma} = a_{n\gamma}^{-1} = \frac{\gamma(1+\gamma)^n}{(1+\gamma)^n - 1}$$

This factor is multiplied by the initial capital costs to give the annualized cost. The annual payment X_a required to pay off a known present value X_P (e.g. a capital cost), over n years, will therefore be as follows:

$$X_a = X_P \frac{\gamma(1+\gamma)^n}{(1+\gamma)^n - 1}$$

Valuation of radiation detriment

General formulation

(85) The components of the total detriment to be considered for valuation include the objective health detriment and other components, such as anxiety over individual levels of exposure and concern on the part of management when individual dose equivalents are significant fractions of authorized limits (see paras. 48 *et seq.*). In the case of occupational exposure, particularly, it may not be automatically assumed that individuals are receiving only small fractions of the relevant limits, and other components of the detriment might have to be taken into account in the valuation of the detriment. It will not always be possible to incorporate such other components into a quantitative optimization.

(86) Optimization assessments can require radiation detriment to be expressed in terms of a cost. In some situations it is appropriate to use the true costs rather than the personal valuations of changes of detriment and, since the objective health detriment is proportional to the collective dose, it is appropriate to conclude that the cost of the objective health detriment, Y_H, is also proportional to the collective dose, S, (see para. 24):

$$Y_H = \alpha S$$

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

This is not an *a priori* assumption. Distinctions should be made between health and economical considerations in the relation between the health detriment and its cost.

(87) When other components of radiation detriment are taken into account, their costs should be added to the cost of the objective health detriment. As indicated in para. 25, if the other components of the detriment taken together depend on individual doses, the cost of the detriment can be expressed in the following general form:

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

where αS is the cost of the objective health detriment as discussed before;

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

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

H_j is the mean dose equivalent to the N_j individuals in the j^{th} group.

The first term in the expression for Y is only related to the collective dose. The second term reflects the possibility that in some complex situations it may be desirable to add the costs associated with additional components of detriment to take account of non-objective features and of non-health detriments.

(88) The optimization techniques, as presented in this report (see paras. 102 *et seq.*), will use both the expression for Y presented in para. 86 and the general expression for Y provided in para. 87 above. However, the algebraic and numerical examples presented in the report will assume that the cost of the detriment is proportional to the objective health detriment (and thus to the collective dose) and will only use the expression for Y presented in para. 86.

(89) The risk factors discussed before (see para. 42 *et seq.*) allow for the prediction of the most important health effects that can result from exposure to radiation. These factors, coupled with the collective dose commitment concept, can give a statistical prediction of the number of cancers and serious hereditary effects occurring as a result of a practice. If by some means it were possible to assign a monetary value to these stochastic health effects, then the value of α could be readily calculated. For example, if a given value could be assigned to each statistical death from cancer, then the value of α would approximately be equal to that value divided by the relevant risk factor for fatal cancer induction as a result of whole-body irradiation. This procedure has considerable appeal because it could lead to a consistent application in a variety of different situations. On the other hand, valuations of statistical death are always involved in safety decisions. Even when the value of life is not explicitly taken into account, an implicit valuation is being done. It should be recognized, however, that the procedure is intrinsically controversial. In the case of radiation protection, a relevant factor to be taken into account in the controversy is the stochastic nature of the potential health effects and the fact that the individuals affected cannot be identified. Thus, any valuation is of *statistical* lives, and not of particular individuals; for example, although the value of the change in life expectancy of unknown individuals is actually being assessed, no value is being assigned to identified individuals.

The valuation of changes in life expectancy

(90) For many years economists and others have studied valuation methods of life expectancy as an aid to decision-making in situations where the allocations of resources can change life expectancy. In practice, these resources are finite and, if they are to be allocated in a fair and consistent manner to different areas of health and safety, statistical life valuations can provide a useful input into the decision-making process. Methods of valuation are reviewed in the literature[9,38,47,48] and it seems appropriate to present a brief review and critique of some of them. The following main methods of valuation will be presented below: human capital approach, publicly implied valuations, court compensation analogies, insurance premium analogies, and national income approach. Individual valuation approaches will also be briefly discussed. Although any of these methods could be used for the valuation of changes in life expectancy, it should be recognized that they are mainly individually-based and might not represent (except for insurance premium analogies and national income approaches) the true cost to society.

(91) A method of valuation of life assumes that individuals are similar to a type of capital equipment whose potential output is lost on its premature demise. The value of life is equated to the value of livelihood as reflected by the individual's loss of future earnings. This technique was the one most frequently used in the past, as it lends itself without difficulty to direct quantification. An equivalent approach, that will be treated separately, considers the loss of national income (see para. 95). However, the consideration of basic economic costs in the context of valuation of life can lead to unacceptable conclusions; e.g. its fixed acceptance could

lead to the conclusion that the premature death of senior citizens confers a net benefit to society. To avoid such unacceptable policy implications, the human capital approach, using net earnings as a measure of net output, is usually augmented by value judgments on social costs. In any case, it should be viewed very much as the absolute minimum sum that should be spent to avoid a premature death.

(92) Although an explicit valuation of life is obviously difficult, it is clear that society already uses a wide range of implicit values through administrative decisions on resource allocation in areas where human lives are at risk. It can also be argued that administrative decision makers, in their role as persons responsive to public opinion, will make decisions from which a true social value of life can be calculated. This assumes that they are perfectly aware of society's needs and do not take short term administratively expedient measures. It further assumes that the range of alternatives presented to decision makers reflects genuine preferences which have been correctly evaluated. Based on these assumptions, life valuations have been derived with a wide range of values. This vast range is perhaps not surprising when the only common denominator between decisions is a reduction in mortality rates, for in reality the decisions were adopted for a variety of reasons. Therefore, the quantitative results derived from this method are likely to be very limited without qualifications and an extensive use of value judgments.

(93) One of the many functions of law courts is to assess damages payable as a result of injury or death and it can, therefore, be argued that the size of awards of damages reflects society's values on compensation. The social costs of premature death could be inferred from the amount of compensation paid to seriously injured individuals whose life expectancies are not altered by the injuries. This measure has been assumed instead of adopting values from awards for death, which strictly only compensate the victim's relatives. While this method has a certain appeal, it also possesses some inherent weaknesses; in many cases compensation is agreed upon, outside the court, and, therefore, the data base can be unreliable. Also, compensation is often awarded under the tort of negligence; that is, if negligence on the part of the victim can be proved, the compensation is reduced. This is a serious drawback in reaching any conclusions about the value of life from court awards.

(94) Another possibility is to analyse the probability of death from engaging in a certain activity. Using data on life insurance premiums paid to cover the risk, it is possible to calculate an implied value of life. However, insurance premia have no direct effect on mortality risks but merely cover the consequences of death by compensating others. It has been pointed out that the fact that a person does not purchase life insurance is not an indication that he does not value his own life.

(95) In some countries a different approach has been used for establishing a tentative value of α and, thus, of statistical life.[40] It is based on the loss of national income plus health and social care expenses due to the death of an average worker.

(96) It appears conceptually possible, in some cases, that some form of individual valuation[38,46,47,48,60] could be incorporated into any monetarization of levels of risk. Where allocation decisions directly affect health and safety, these valuations should be based in some way on either the amount individuals are prepared to pay for a decrease in risk or, conversely, the amount they would accept in compensation for an increase in risk. In principle, such individual valuations are directly measurable by survey techniques, but, given the difficulties in interpreting the results of surveys, indirect methods are often used to attain such valuations.

The value of α

(97) Over the years there have been a number of attempts to define a value of the unit collective dose so that estimates of collective doses could be conveniently converted into

monetary units. Without correcting prices to any particular year the values have ranged from approximately US$1 000 per man sievert to approximately US$100 000 per man sievert.[1,11,12,16,21,41,43,49,56,58,59,62,73] No firm conclusions could be drawn from this range, apart from showing that, over the years, different individuals and organizations had used various methods to produce different values for the unit collective dose. Furthermore, some individuals and organizations have proposed using different values for radiation workers and for the general population, and for routine operations versus abnormal situations. However, it should be mentioned that, in many cases where a wide range of values has been proposed, these values were derived within a conceptual framework clearly different from the one presented in this report. In the numerical examples given in this report, values of α in the range of 10 000 to 20 000 $ per man sievert have been used.

Distributional problems

(98) Most radiation practices give rise to distributional problems; e.g. people incurring the detriment from the practice would not necessarily receive the benefit in equal degree. *Spatial* distributional problems may occur if people in areas other than those where the practice is performed incur part of the costs from the practice. On the other hand, costs occurring at times different from those of the practice give rise to *temporal* distributions. It might be considered necessary to adjust valuations of costs in the light of distributional problems. The problem of costs, detriments and benefits distributed over different populations at different times is complex, at least from an ethical viewpoint. There may also be political and legal complexities, so only general guidance can be given here.

(99) The objective health detriment, as used in optimization procedures, has been based on the collective dose incurred by *all* persons receiving a non-zero dose from a practice. Thus, in the case of dispersion of radionuclides which cross national boundaries, the value for α used in the optimization process should be applied to all doses received, without regard to location. However, the value of α might differ from country to country. The relevance of this problem could be decreased if some internationally acceptable minimum limit for the value of α could be selected and adopted for application to the international component of the collective dose. In any case, the value of α should not be lower, when applied to other countries, than the value applied within the source country.

(100) Distributional problems associated with costs and detriments occurring over different time periods are likely to be frequent in radiation protection, especially when a practice leads to environmental contamination by long-lived radionuclides which might also expose future populations. The concept of collective dose commitment allows for the calculation of the detriment in these cases because the upper limit of the time integral is infinity. Nonetheless, as shown in para. 55, the quantity incomplete collective dose commitment can be used in some formal optimization assessments; e.g. when different radiation protection strategies and technologies having limited lifetimes are compared.

(101) Methods of comparing costs at different times often use discounting techniques. The possibility of discounting future detriment costs is much more controversial and the time-span over which the detriment cost is spread is often very much greater than is the case for the cost of protection. Although the use of discounting of detriment cost does not change the principles described in this report, the use of conventional discounting techniques makes very substantial changes in the quantitative results. National authorities wishing to use any form of discounting of detriment costs should therefore consider carefully the practical implications of any such use.[10,13,73]

Quantitative Techniques for Optimization

The ideal optimization case

(102) Only one exposed population group and one radiation protection parameter (or a simple set of radiation protection options) can be considered in an ideal optimization case. A quantitative relationship can also be assumed between the collective dose commitment, S, and the maximum individual annual effective dose equivalent, H^*:

$$H^* = F(S)$$

(103) By introducing the expressions of the cost of the detriment (see paras. 86 and 87) into the objective function presented in para. 68, this function can be expressed either as:

$$U = X(\omega) + \alpha S(\omega) = \text{minimum}$$

or as:

$$U = X(\omega) + \alpha S(\omega) + \beta \sum_j N_j f_j[H_j(\omega)] = \text{minimum}$$

depending on whether the component of the detriment associated with the individual dose distribution is or is not taken into account.

(104) Using the previously-defined symbol, optimization in the ideal case may therefore be expressed with the following set of conditions:

(i) $$X(\omega) + \alpha S(\omega) = \text{minimum}$$

or

$$X(\omega) + \alpha S(\omega) + \beta \sum_j N_j f_j[H_j(\omega)] = \text{minimum}$$

(ii) $$X = X(\omega)$$

$$S = S(\omega)$$

and,

(iii) $$F(S) \leq H_L$$

(105) The minimum for the objective function can be obtained by differentiation and making the result equal to zero. Depending on the objective function that is used, the result will be:

$$\left.\frac{\mathrm{d}X}{\mathrm{d}\omega}\right|_{\omega_o} = -\alpha \left.\frac{\mathrm{d}S}{\mathrm{d}\omega}\right|_{\omega_o}$$

or

$$\left.\frac{\mathrm{d}X}{\mathrm{d}\omega}\right|_{\omega_o} = -\alpha \left.\frac{\mathrm{d}S}{\mathrm{d}\omega}\right|_{\omega_o} - \beta \sum_j \left.\frac{\mathrm{d}[N_j f_j(H_j)]}{\mathrm{d}\omega}\right|_{\omega_o}$$

where ω_o is the optimized protection parameter.

(106) The value of the collective dose, S_o, corresponding to the optimized radiation protection parameter, ω_o, must comply with the limit equation, $F(S_o) \leq H_L$. Therefore, for this ideal case, optimization is achieved at a value of collective dose commitment, S_o, such that one of the above differential equations is satisfied, provided that

$$F(S_o) \leq H_L$$

Thus, if $F(S_o) \leq H_L$, the value of S_o must be selected at a value $S_o \leq F^{-1}(H_L)$. This approach assumes an invariable relationship between individual doses and collective doses (which is the case when operation practices cannot be altered and only changes in design are feasible). Cases may occur, however, where the dose-limit restriction can also be achieved by changing the form of the function F (see paras. 129 and A-11).

(107) In some assessments of optimization, the identification of a unique, continuously-variable radiation protection parameter is not feasible, but different protection options, not necessarily defined by a single parameter, are available. The changes in protection levels are achieved with finite increments of X and S, from an option to another, both X and S being discrete values rather than continuous variables. The decision of going from a level of protection, A, to a more costly one, B, would be indicated if:

$$-\frac{{}_{\mathrm{B}}X - {}_{\mathrm{A}}X}{{}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E} \leq \alpha$$

or

$$-\frac{{}_{\mathrm{B}}X - {}_{\mathrm{A}}X}{{}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E} \leq \alpha + \beta \sum_j \frac{{}_{\mathrm{B}}N_j f_j({}_{\mathrm{B}}H_j) - {}_{\mathrm{A}}N_j f_j({}_{\mathrm{A}}H_j)}{({}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E)_j}$$

where the subscripts A and B indicate that the relevant variable appertains to the corresponding option.

(108) In these cases, optimization can be achieved through an iteration process, testing increasingly higher levels of radiation protection, and stopping at the point required by the above equation. Usually the selected dose upper bound can be respected by starting the analysis with an option providing sufficient radiation protection for the most exposed individual. When many alternatives are available and arranged in increasing order of cost, before deciding to discontinue the search for an optimum alternative (since the conditions shown in the above paragraph do not apply), it would be convenient to ascertain that the conditions do not apply for other possible changes in the level of radiation protection. The optimum condition, therefore, will be that for which any jump to another option will not comply with the equation in para. 107. When only the objective health detriment is taken into account, the optimum level can be easily found by a simple method involving a graphical procedure. First, all the alternative possibilities defined by their cost, X, and collective dose commitment, S^c_E, values, have to be plotted on an X versus S^c_E plane of ordinate axis. Then, a straight line, with a slope equal to $-\alpha$, has to be moved from the lower left to upper right. The first represented point which is touched by the line is the optimized solution. Another simple method to identify the optimum option is to calculate the sum of cost of both protection and detriment, $X + Y$, for each option and then to select the option which yields the smallest sum.

Optimization of complex systems

General formulation

(109) When several components of the radiation protection system have to be simultaneously optimized and each component contributes to the radiation protection of several exposed groups of people, optimization assessments are seldom carried out by simple differential cost–benefit analysis. The solution of the objective function, as bounded by the constraining functions and limit equations, becomes more complex. This general case will be discussed in this section.

(110) If exposures from a given source or practice can be regarded as being composed of

contributions from several subsystems, ℓ, each requiring appropriate radiation protection measures, optimization implies any of the following objective functions:

$$\sum_{\ell}(X_{\ell}+\alpha S_{\ell})=\text{minimum}$$

or

$$\sum_{\ell}[X_{\ell}+\alpha S_{\ell}+\beta\sum_{j}N_j f_j(H_{j\ell})]=\text{minimum}$$

where X_{ℓ} is the cost of radiation protection of subsystem ℓ;

S_{ℓ} is the collective dose commitment resulting from subsystem ℓ; and

$H_{j\ell}$ is the mean dose equivalent to the N_j individuals in the j^{th} group from subsystem ℓ.

Independent subsystems

(111) Optimization procedures for complex systems are no more difficult than the ideal case if the subsystems are independent. The constraining functions can be readily established when the subsystems ℓ are independent, in the sense that the control exercized in one of them does not influence the collective dose commitments from the others.[5]

(112) In this case, differentiating the general objective functions with respect to each S_{ℓ} and setting each resulting function equal to zero, the following set of equations is obtained for $\ell=1, 2, \ldots$:

$$\frac{\partial X_{\ell}}{\partial S_{\ell}}+\alpha=0$$

or

$$\frac{\partial X_{\ell}}{\partial S_{\ell}}+\alpha+\beta\sum_{j}N_j\frac{\partial f_j(H_{j\ell})}{\partial S_{\ell}}=0$$

because for all $X_{\ell'}$ and $S_{\ell'}$, where $\ell'\neq\ell$, the derivatives on S_{ℓ} are equal to zero

$$\frac{\partial X_{\ell'}}{\partial S_{\ell}}=0 \qquad \frac{\partial S_{\ell'}}{\partial S_{\ell}}=0$$

due to the independence of the subsystems.

(113) As individual annual doses should not exceed the authorized limit, a set of limit equations is obtained:

$$\sum_{\ell}F_{\ell}(S_{\ell})\leq H_L$$

It follows, from both sets of equations, that the optimization can be obtained by optimizing each independent subsystem taken separately.[5] Similarly, the optimization for the combined exposures from several installations at a given site can be obtained by optimizing separately the radiation protection at each installation, provided the condition of independence applies.

Interrelated subsystems

(114) In cases where the subsystems are not independent, optimization procedures can be highly complicated. The radiation protection to be optimized can conceptually be divided into subsystems $\ell=1, 2 \ldots n$, while the exposed group can be considered as being composed of

subgroups $j=1, 2 \ldots k$. The collective dose commitment caused by a given subsystem in a given subgroup is denoted $S_{\ell,j}$. The maximum annual effective dose equivalent in a given subgroup caused by a given subsystem is designated $H^*_{\ell,j}$. The subsystems and subgroups must be selected in such a manner that there is a defined relationship between $S_{\ell,j}$ and $H^*_{\ell,j}$ that is

$$H^*_{\ell,j} = F_{\ell,j}(S_{\ell,j})$$

In the extreme case, each subgroup might correspond to a single individual.

(115) Under the conditions described in the previous paragraph, optimization can be formalized by the following sets of relations:

(i) Objective functions

$$\sum_{\ell} (X_\ell + \alpha \sum_{j} S_{\ell,j}) = \text{minimum}$$

or

$$\sum_{\ell} [X_\ell + \alpha \sum_{j} S_{\ell,j} + \beta \sum_{j} N_j f_j(H_{j,\ell})] = \text{minimum}$$

(ii) Constraining functions

$$S_{\ell,j} = \psi_{\ell,j}(X_\ell)$$

(iii) Limit equations

$$\sum_{j} F_{\ell,j}(S_{\ell,j}) \leq H_L$$

(116) If the number of subsystems and subgroups is small, the solution can be obtained analytically[39] (e.g. by the use of Lagrangian multipliers). However, in most cases, the number of variables will be too large and more sophisticated computational techniques will be required.[63] Since there is no such thing as a universal optimizing technique, the choice of a particular method should depend on the system being considered and on the computation resources available. In some cases the system can only be modelled by using non-linear equations and non-linear programming, or dynamic programming methods might be required. These optimization techniques are currently used, to varying degrees, in design engineering[63] and economic planning. The choice and complexity of the method depends on the system being considered and no general guidance can be given.

(117) The methods that have been presented describe the formalistic approach recommended by the Commission on the use of cost–benefit analysis for optimizing radiation protection in order to keep doses as low as reasonably achievable, maintaining—as far as possible—a distinction between objective and subjective considerations. The level of radiation protection resulting from the application of these methods is theoretically optimum as far as radiation protection is concerned, within the framework of cost–benefit analysis techniques. However, in practice, the final decision on the actual level of radiation protection might require further consideration by the decision makers, and other criteria and parameters, not necessarily related to radiation protection, might require special attention. There are methods, other than those presented in this report, that can be used for decision-making in radiation protection (see paras. 4, 5 and 9 *et seq.*).[45]

C. THE PRACTICAL USE OF COST–BENEFIT ANALYSIS IN THE OPTIMIZATION OF RADIATION PROTECTION

(118) The cost–benefit techniques developed in Section B are analytical tools addressed to designers, operators and decision makers, which can be used for optimizing radiation protection. They should not only be concerned with radiation protection systems able to ensure respect for individual dose limits, but with design and operational conditions liable to keep doses as low as reasonably achievable. Although the methods introduced in that section are aimed at this objective, their practical use may present some difficulties. The practical use of cost–benefit analysis techniques for optimizing radiation protection is discussed in this section and some algebraical and numerical examples are presented.

(119) The analytical techniques exemplified in this section are only a part of the complex process involved in deciding the levels of radiation protection. The examples do not include all the problems related to the decision-making process on the ultimate level of radiation protection, which, for many reasons, can be more conservative than the optimum resulting from a cost–benefit analysis. Moreover, the examples will ignore cases where the parameters are uncertain and only intuition might be employed. Intuitive optimization is implicitly applied when simple decisions affecting protection in operations are made, usually on the simple basis of good engineering judgment.

Optimization of Radiation Protection through Design

(120) Many variables should be considered when optimizing radiation protection through design. Some are design variables, both controllable and uncontrollable. The former are parameters that the designer can always adjust, i.e. exposure control parameters (such as shielding thickness and ventilation flow rate) which could be conceptually designed to the required level of radiation protection. The latter are, *a priori*, non-modifiable quantities; common examples of these are the intrinsic properties of shielding materials (which, although formally liable to be subject to control by choice of material or composition, cannot be altered in many practical cases), and the temperature of outside ventilating air. The designer will also deal with quantities (e.g. the voltage of ventilation blowers, the activity of the source) which define a condition in the design, and with external conditions such as the environmental features relevant for the radiation protection system. Finally, there are also parameters which might vary over time. The examples of optimization of design presented in this section will only deal with the optimization of controllable design variables; it is assumed that all other parameters are design conditions and not subject to the optimization process.

(121) Practices involving ionizing radiation might be required to be performed in complex installations which generally include multiple systems for controlling the exposure of people. In these cases optimization of the overall design of radiation protection can become a rather complicated process. Further complications will be introduced if the systems are not independent or when the exposure control parameters do not affect both maximum individual and collective doses by the same factor. In many cases, however, radiation protection is achieved with a single control device or by using independent systems which rely on control parameters affecting proportionally both individual and collective doses. Only examples of those simplified cases will be attempted in this section, although a simple, formalistic example is also presented (see Appendix A, para. A-11) where the individual dose distribution is assumed to change through the optimization process.

(122) Even for the simple cases where a single control option is considered, a two-step

optimization approach should be used, as follows: a decision on the most cost-effective way to control exposure should be made first, and, afterwards, the selected control parameter should be optimized. It should be noted that, for the examples shown in this section, the control parameter was selected without any specific preliminary analysis.

(123) Radiation protection makes use of technological features for controlling exposure of patients, of workers and of the general public. In optimization assessments, proper attention should be paid to the interactions between the group to which radiation protection is primarily addressed and other exposed people. For example, reduction of environmental releases, which would primarily benefit the public, might increase occupational exposures and vice versa. Such considerations are not introduced in the examples in this section.

(124) A relevant factor in optimization assessments is the dosimetric model used for the determination of collective doses. In order to ensure the limitation of individual doses, a common practice is to use conservative dosimetric models. In the case of optimization assessments, however, realistic models should be used, so as not to introduce an undue bias in the calculations. In the examples presented in this section, the dosimetric models are intended to be as realistic as possible.

(125) Within the limitations indicated in the above paragraphs, this section will include some design examples of systems for protecting against external irradiation and internal contamination, and for controlling the release of radioactive materials into the environment. The algebraical treatment is included in appendices to this section and some simplified numerical examples are included in annexes. The main aim of the examples is to show that the optimization methods presented in Section B are feasible to be implemented. The intention is not to consider all practical solutions and difficulties of optimization of design, nor to recommend specific techniques for radiation protection. It is emphasized that the optimized parameters resulting from the examples were only intended for demonstration and should not be interpreted as being recommended by the Commission. Moreover, the numerical examples are specimen values only and, therefore, the results should not be interpreted as representative of the situation described in the example.

Examples of Optimization of Radiation Protection through Systems Intended to Protect against External Irradiation

(126) Strategies for controlling exposure to external irradiation include: (a) modification of the characteristics of the source of radiation (e.g. its activity); (b) variation of the distance between the source and the exposed people; (c) operational procedures, such as modifications of exposure time; and (d) shielding of the radiation beam. Consequently, the collective dose incurred by people exposed to external irradiation and the cost of the radiation protection will be related to the associated controlling parameters, such as: the activity of, and the distance from, the source; the thickness and the attenuation coefficient of shielding; and the temporal occupancy of exposed people. In principle, each one of these parameters can be continuously modified and an optimum set of values can be determined. In practice, however, some of these parameters are, *a priori*, non-modifiable, at least, easily.

(127) The activity of the source of radiation is usually an uncontrollable parameter, although, in some cases, it might be subjected to the optimization process; e.g. the activity in the primary and other ancillary systems in nuclear reactors can be controlled by decontamination and the relevant control parameters might be optimized. The distance from the radiation source to exposed individuals is another parameter that is difficult to change but which might, in principle, also be optimized. In practice, the shielding thickness and working practice features

appear to be the main control parameters which can usually be selected to optimize radiation protection when external radiation is present.

Example of optimization of radiation protection through the design of a simple shield

(128) A method for optimizing the protection for a shielded source of radiation will be presented as an example.[4,5] The thickness of a simple planar wall shield will be used as the single control parameter, although any other variable affecting both cost of protection and detriment will do equally well (e.g. any variable related to working practices, such as the number of people being protected by the shielding (see paras. 160 *et seq.*). Instead of applying limit equations, for the purpose of the example, an idealization of the design will be assumed such that the minimum thickness of the shield would have to be sufficient to ensure compliance with the authorized individual dose limit, even under conservative conditions such as the receptor being continuously in contact with the shield surface. Thus, the optimization process will start from an initial (minimum) shield thickness which, ensuring that an ideal individual exposed to the highest doses will comply with the limits, automatically ensures that no individual in the group will exceed the limits. This initial design condition may be excessively restrictive. If the design dose rate resulting from the optimization process is far below a limiting dose rate derived from the relevant authorized dose limit (e.g. far below 25 μSv h^{-1} for occupational exposure) no other considerations are needed. If, on the other hand, the resulting dose rate is near the limiting condition, the result can be prejudiced and a limit equation should be introduced in the optimization process. Limit equations will not be included in the mathematical formulation of this example.

(129) Workers exposed to radiation fields actually incur doses lower than the potential dose which might be received at the shield surface. There are indications that, in some cases, the actual individual doses can be described by a log-normal distribution in the range of doses well below the dose limits.[69] Although there is no justification for assuming that this distribution is associated with any single operation, for the purpose of the example it can be assumed that a constant ratio exists between the average and the maximum individual dose. It may also be assumed that the optimization of the shield thickness will imply changes on the level of individual doses but not on the dose distribution. A constant ratio, ρ, between average and maximum dose rate will be basically used in the example; however, a formal assessment is also presented assuming a variable individual dose distribution (see Appendix A, para. A-11).

(130) It may also be assumed that a simple exponential relationship exists between dose rate and thickness. If the ratio ρ is constant, the average dose rate (and the collective dose rate) will be exponential with respect to the thickness of the shielding. Therefore, using the formulation of para. 86, the cost of detriment, Y, may be assumed to have an exponential relationship to the shielding thickness. The algebraic formulation is developed in Appendix A and results in the following expression:

$$Y(w) = \alpha N f_t \tau \rho \dot{H}_u \, e^{-\Gamma w}$$

where α is the dimensional constant expressing the cost assigned to the unit collective dose;

N is the number of exposed individuals;

f_t is the occupancy time factor;

τ is the lifetime of the installation;

ρ is the constant ratio between average and maximum dose rates;

$\dot{H}_u$ is the maximum effective dose-equivalent rate which would be incurred by a hypothetical receptor located in contact with the external face of the initial minimum thickness shield (in practical shielding design, $\dot{H}_u$ can be taken to be the maximum dose-equivalent rate at the point of occupancy being considered outside the shielding)—in any case $\dot{H}_u \leq \dot{H}_L$;

Γ is the effective attenuation coefficient; and

w is the shield thickness, $e^{-\Gamma w}$ being the dose reduction factor.

(131) The cost of a shield includes the cost of the installed shielding materials and the cost of support installation. For the purpose of the example, the operational costs may be neglected, as they are considered substantially lower than the cost of a shield. Therefore, it may be assumed that over the range from minimum to optimum thickness the cost of the shield, X_S, will vary proportionally with the amount of shielding material as follows:

$$X_S = X_V V_S + X_I$$

where X_V is the cost per unit volume of shielding material installed;

V_S is the volume of shielding material; and

X_I is the support installation cost which, for the purpose of the example, is assumed to be constant with thickness within a small range of thickness variation.

(132) Since the volume of shielding material is proportional to the shielding thickness, the cost of a rectangular planar shield will have a linear relationship with the shield thickness, as follows:

$$X(w) = X_V hlw + X_I$$

where h is the shield height;

l is the shield length; and

w is the shield thickness.

(133) Once the constraining functions have been established, an optimized dose reduction factor for this example can be derived by following the procedure introduced in Section B. The algebraic formulae are presented in Appendix A. The result shows that the optimized dose reduction factor turns out to be directly proportional to the cost of unit volume shield and inversely proportional to the following parameters: the lifetime of the shield, τ; the selected value of α; the effective attenuation coefficient, Γ; the maximum effective dose-equivalent rate, $\dot{H}_u$; the occupancy factor, f_t; the number of people per unit shield area, N/hl; and the ratio between average and maximum individual doses, ρ; so that:

$$e^{-\Gamma w_o} = \frac{X_V hl}{\tau \alpha \Gamma \dot{H}_u f_t N \rho}$$

The resulting optimized extra shield thickness, w_o, can be derived from the above expression. Thus, the optimized shield thickness will be equal to the sum of the initial thickness plus the extra thickness.

(134) A numerical example based on the formula in para. 133 is presented in Annex A_1. Formulation of optimized reduction factors for more complicated cases are developed in Appendix A. It should be noted that the thickness of shield obtained in the examples might have

been made up of several different materials offering different costs and benefits. It would then have been formalistically appropriate to regard their selection as a part of the optimization process and not as part of the cost effectiveness analysis that should have preceded it.

Examples of Optimization of Radiation Protection through Systems Intended to Protect against Internal Irradiation

(135) People working in areas where airborne contamination is present become exposed not only to external radiation from the source but also to radiation from materials taken into the body. The exposure due to external radiation caused by the dispersed material may sometimes be neglected, because this is generally a minor contributor to the dose commitment. Since radioactive materials are taken into the body mainly by inhalation of materials dispersed in air, optimization can be effectively performed through the control of the concentration of airborne radioactive material in air.

(136) Several radiation protection techniques are available for controlling airborne contamination. Some examples are: source isolation; ventilation, including air cleaning; and respiratory and whole-body radiation protection. The last two techniques will not be discussed in this section, since they can basically be considered an operational procedure.

(137) When there is a possibility of contamination with radioactive materials arising from a given source, the first method of radiation protection usually employed is the confinement of the source by either: (i) static isolation, where radioactive material is confined by a physical barrier (e.g. glove boxes, hot cells); or, (ii) dynamic isolation, where confinement is obtained by means of some aerodynamic system (e.g. radiochemical hoods). In some cases, both static and dynamic isolations can be jointly used (e.g. boxes and cells operated at a negative pressure differential). The cost of static isolation usually depends on the leakage rate through the physical barrier and, conceptually, it can be quantifiable. Dynamic isolation is commonly achieved by establishing pressure gradients across the physical barrier to ensure an air flow into the potentially contaminated areas. The control parameter is the pressure gradient across the isolation boundary and is related to the energy required to maintain the air flow through the openings. The cost of dynamic isolation could be assessed on the same basis as the cost of ventilation (see paras. 143 through 145). The relationship between leakage rates from both static and dynamic containments and derived exposures is too complex to be established in advance, thus making it difficult to perform an *a priori* optimized design. Optimization of isolation, however, could be achieved retrospectively.

(138) Examples of optimization of ventilation and air cleaning are presented in paras. 140 *et seq.* As these radiation protection techniques are usually independent of other radiation protection systems, they can be optimized individually. The controlling parameters are the air-flow rate and the decontamination efficiency, both assumed to affect individual and collective doses by the same factor.

(139) Optimization of ventilation systems giving radiation protection from exposure to radon and radon daughters has been considered in some detail in appendices. The examples include a discussion of the basic methods of optimization as well as more general aspects of radiation protection. The mathematical sophistication of the radon examples is related to the assessment of the contamination due to radon and its progeny itself, rather than to the optimization process.

Examples of optimization of radiation protection through the design of ventilation and air cleaning

(140) If the natural ventilation of a confined space proves to be unable to control the

contamination of air, mechanical ventilation should be introduced. Simple ventilation systems generally operate by blowing fresh clean air through the confined environment at a given rate, decreasing the concentration of radioactive material in air and thus the radiation exposure. In simple once-through systems, the controlling parameter is the air flow rate.

(141) For the purpose of this chapter, simple ventilation systems are assumed to include intake filters, fans and ventilation ducts. The exhaust-filter system may be assumed not to be a part of the ventilation system but a system in itself intended to limit the release of radioactive material in gaseous effluents (see Optimization of Radiation Protection through Systems Limiting Environmental Releases of Radioactive Materials, paras. 154 *et seq.*).

(142) The collective dose, and thus the cost of detriment, incurred by the people staying in a confined space will be proportional to the remaining concentration of radioactive materials in air. The related formulation is presented in Appendix B, paras. B-1 and B-2, and shows that this concentration varies inversely with the ventilation flow rate. The cost of the detriment will therefore become inversely proportional to the ventilation flow rate, as follows:[20]

$$Y = \alpha N f_t \tau F_d \frac{\dot{A}}{Q}$$

where α is the dimensional constant expressing the cost assigned to the unit collective dose;

N is the number of exposed individuals;

f_t is the occupancy time factor;

τ is the lifetime of the installation;

F_d is a dosimetric factor converting activity concentration into dose rate (i.e. the effective dose-equivalent rate incurred by exposed individuals, per unit concentration of radioactive material in air), which is assumed to be an average value corresponding to the mean age of the exposed people;

$\dot{A}$ is the constant input rate of radioactive material into the confined space; and

Q is the ventilation flow rate.

(143) The cost of ventilation includes the cost of the system, the cost of its operation and other costs related to its installation (e.g. modifications of the structures, which might be needed to accommodate the ventilation system). For the purpose of the examples, the cost of operation will be assumed to be the dominant component of the cost of the system. This assumption will be realistic if the ducts are not very long and if alterations to the building are unnecessary. On the other hand, although changes in the air flow rate can modify the cost of the system, the cost will remain practically constant with respect to the flow rate if only minor modifications are introduced in the flow rate by the optimization process. In some cases, however, these conditions do not apply. In mines, for instance, the ducts and shafts can be very long and the cost of installation of ventilation systems might not be negligible if compared with the running costs (see Annex D_1).[64] In dwellings, where normally very low flow rates are used, operating costs are usually lower than installation costs.

(144) The operating cost of ventilation includes the cost of the energy needed to circulate and, when necessary, to condition the air; the latter cost can in some cases be predominant. Other components of the operating cost, such as the cost of maintenance materials and wages, will be, for the purpose of the examples, assumed to be negligible if compared with the energy cost. In ventilation systems with a laminar (i.e. streamline) flow, there is a linear relationship between

the pressure drop and the flow rate. The relation becomes quadratic for a turbulent (i.e. eddy) flow. The power needed in the shaft of the fan system will theoretically be proportional to either the square, or the cube, of the flow rate (depending on whether the flow is laminar or turbulent), and also to the efficiency, which, in turn, is a function of the flow rate. In practice, as a result of the combination of all the factors involved, the electrical energy expended per unit mass of air circulated through the system can, in some cases, and will for the purpose of the example, be assumed to be approximately constant. The values found in some actual ventilation systems are in the order of a few kilojoule of electric energy per cubic metre of circulated air.[20,64] On the other hand, as the energy required to condition a given mass of air is also constant with the air flow, the total energy required can be taken to be approximately proportional to the amount of air moved by the ventilation system during its operation. Since the cost of electricity per unit energy is constant within a wide range and the total amount of air is proportional to the flow rate, it will in summary be assumed, for the purpose of exemplification, that an approximately linear relationship exists between the cost of operating a ventilation system and the air flow rate.

(145) Provided the operating cost over the lifetime of the plant is assumed to be predominant and if the conditions assumed above apply, the cost of ventilation, X_v, will be:

$$X_v = abf\tau Q$$

where Q is the ventilation flow rate;

a and b are constants representing the cost of electricity per unit of electrical energy, and the energy expended to condition and circulate a unit volume of air, respectively;

τ is the life-time of the system; and

f is a factor representing the fraction of time in which the system operates.

If full occupancy is assumed during the operation of the system, f will be equal to f_t. The assumption of constant b should be used with caution because it can be unrealistic, particularly in installations with a rather small "equivalent orifice".

(146) Under the assumptions above, the optimum flow rate, Q_o, can be derived for a simple case of ventilation with operating costs dominant. The algebraic formulation of this simple, non-specific ventilation system is developed in Appendix B. The optimum flow rate turns out to be a square root function of the following parameters: (i) the constant input rate of radioactive materials into the confined space, $\dot{A}$; (ii) the number of exposed people, N; (iii) the dosimetric factor, F_d; and, (iv) the volume of air which is worthwhile replacing in order to save a unit collective dose, α/ab, so that:

$$Q_o = \left(\frac{\alpha}{ab} N F_d \dot{A}\right)^{1/2}$$

Two numerical examples based on the above formulation are presented in Annex B_1. The mathematical treatment of cases where b is not constant would be the same but the exponent of the function Q_o can be lower than 1/2.

(147) The algebraic example developed in Appendix B describes a simplified idealized situation. It does not, for instance, consider localized concentration gradients. In some instances a limited number of workers with a special task could be subjected to potentially high concentration in the immediate vicinity. In these particular cases the individual dose and the collective dose may be altered in quite different ways by increasing the air flow. In these cases the radiation protection might preferably take the form of local air treatment rather than that of increased overall ventilation. The formalistic treatment of optimization in these cases is, in

principle, the same but it would search for an optimum value for each flow rate ventilating different areas in the same environment.

(148) Also, the example ignores the fact that, in particular cases, an increased ventilation rate does not necessarily lead to improved radiation protection. For instance, if very shortlived radionuclides are released a great distance from potentially exposed persons, radioactive decay during the long transit time might be sufficient to limit the exposures to insignificant levels. However, if the transit time (and attendant decay) is reduced by some mechanism, such as increasing the air flow rate (and thus the air velocity between the source and the potentially exposed persons), the exposure levels could actually be increased.

(149) Furthermore, the simplified example presented in Appendix B does not consider changes in the isotopic composition of the airborne radionuclides between the point of release and the point of exposure. When a radionuclide becomes airborne and its decay produces radioactive daughter nuclides which in turn decay leading to further generations of daughters, the analytical models describing the concentrations of each of the several nuclides in air can be complex. Each radioactive nuclide has a unique decay rate, the source of the parent nuclide can have a variable release rate, and the residence time in the confinement space varies by changing the ventilation flow rate. Optimization of ventilation of environments contaminated with radon-222, for instance, presents these special problems. Radon-222 is a naturally-occurring radionuclide produced by decay of radium-226. It can diffuse into the air from soil, building materials, water and other materials in which it exists. Radon-222 decays to daughters which are the primary contributors to the dose delivered to the respiratory tract from intake by inhalation. The concentration of radioactivity in air contaminated with radon-222 varies not only because of dilution in the fresh air introduced by a ventilation system, but also because of changes in the radioisotopic composition of radon daughters during their transit time through the ventilated space.

(150) Although optimization of ventilation in cases with radon contamination can also be conceptually performed using the method presented in Appendix B, the algebraical treatment and the resulting equations are inevitably more complicated. The particular relevant quantities to be considered in the optimization assessment are the potential alpha energy of radon and its daughters, the equilibrium factor of radon daughters and the equilibrium equivalent concentration of radon. A discussion on the problems and uncertanties related to these quantities, with reference to optimization, is presented in Appendix C. A further problem in assessing exposure to radon and its daughters is the uncertainty in the estimation of the collective doses. A brief discussion on the dosimetric (dose conversion) factors, which may be used in quantifying collective doses from exposure to radon, in optimization assessments, is presented in Appendix C.

(151) Appendix D presents a simplified algebraic treatment for optimizing the ventilation flow rate in spaces with radon contamination and a more complex formalistic example of optimization of ventilation of uranium and other mines through design. A derived numerical example is presented in Annex D_1, outlining a procedure to backfit ventilation systems already installed in uranium mines.

(152) If ventilation systems include air cleaning, further complications would be introduced into the optimization process. Air cleaning is a particular ventilation technique used to decontaminate air in close environs. Basically, air cleaning systems operate as a closed-circuit ventilation system. A fraction of contaminated air is extracted from the working environment and decontaminated, usually by filtering or other methods of removal of the radioactivity. Once cleaned, the air is again injected into the working environment. This recyling can also be partial, e.g. some of the air changed could be fresh and some recycled.

(153) The mathematical formulation of optimization of air cleaning is basically the same as that of ventilation. However, other parameters must also be taken into consideration, namely, the total efficiency of decontamination of the system cleaning the air (e.g. filtering or other removal system) and the fraction of air recycled. Appendix E presents the algebraical treatment of a simple example of air cleaning which assumes full recirculation. The cost of radiation protection is determined on the same basis as the cost of ventilation, but further assuming that the operating cost of the system decontaminating the air is proportional to the number of the decontamination units (e.g. each filter) used. A set of optimal combinations of flow rate and number of decontamination units is obtained for the example.

Optimization of Radiation Protection through Systems Limiting Environmental Releases of Radioactive Materials

(154) It is possible to alter the doses from exposure to radioactive materials in effluents by several procedures: (i) the release mode can be changed; e.g. a change in the height of gaseous releases can alter the dispersion of the effluent in the near vicinity of the release location; (ii) the release of effluent can be delayed; e.g. the use of delay tanks can alter the relative composition and activity of the radioactive material in the effluents due to decay of the nuclides; (iii) the amount of radioactive material released can be reduced by partial removal of material from the effluent stream by filtration or other treatment. In the case of long-lived radionuclides, control of exposures can be achieved by removal of the radionuclides from the effluent stream, retention of the captured material, and disposal by a method which would ensure isolation of the material from the environment for some significant period.

(155) The analysis of the control technology requires detailed knowledge of the design of the installation in which it is to be employed. Each process step must be analysed to identify radionuclide inventories, mechanisms and pathways for radionuclide releases in the environment, volume flow rates, and the physical and chemical characteristics of the process stream. Although modifications of the release techniques influence doses to individuals near the release point, in many cases such modifications are unable to alter significantly the collective dose due to the release and play an unimportant role in the optimization process. For instance, optimization should obviously not only be applied to the stack height but also to the cleaning of gaseous effluents; however, if changing the stack height does not significantly alter the collective dose, then optimization will provide no support for high stacks. Only systems which reduce releases by delay and consequent radioactive decay, and remove material from the effluent stream, will be discussed as examples.

(156) The relevant parameter of continuous release systems controlled by decay is the transit time of radionuclides from their origin until they are released to the environment. This transit time is governed by the relation between the volume available for decay and the effluent volumetric flow rate. The reduction factor applied to the release can be calculated for each relevant nuclide i by

$$\mathrm{fr} = e^{-(\lambda_i \upsilon_D / Q)}$$

where fr is the fraction of the original radioactive source which exists at time υ_D/Q;

λ_i is the radioactive decay constant of the nuclide i;

υ_D is the available volume for decay; and

Q is the volumetric flow rate.

(157) Removal processes for any specific mode of effluent release can be specified for each relevant nuclide i by a decontamination factor, D_i, defined by the relation:

$$D_i = \frac{C_{E_i}}{C_{I_i}}$$

where C_{I_i} is the concentration of nuclide i in the incoming process stream; and

C_{E_i} is the concentration of nuclide i in the effluent process stream.

For a given initial effluent composition, defined by the annual potential released activities of each nuclide, $\mathring{A}_i$, the collective dose commitment, S^c_E, would be given by:

$$S^c_E = \tau\left(\sum_i s_i \mathring{A}_i D_i + \dot{S}_{E,O}\right)$$

where s_i is the collective dose commitment per unit activity of nuclide i released;

τ is the lifetime of the installation; and

$\dot{S}_{E,O}$ is the annual collective effective dose equivalent due to occupational exposures from the control system; in some cases, this term contributes little to the collective dose commitment.

(158) In most practical assessments of optimization of release control, the changes in control levels are achieved by finite increments provided by control options, both X and S^c being discrete and not continuous variables.[4–6,25] The S^c_E decision of going from a level of control A to a more costly level of control B would be taken if:

$$-\frac{{}_{\mathrm{B}}X - {}_{\mathrm{A}}X}{{}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E} \leq \alpha$$

In these cases optimization can be achieved by any of the processes described in para. 108.

(159) Appendix F presents a practical procedure for the optimization of release control. Annexes F_1 and F_2 introduce two numerical examples which use the procedure given in Appendix F. The first example relates to the optimization of control of short-lived gases from a boiling water reactor. The second one presents a case of optimization of control of iodine-129 in effluents from a reprocessing plant.

Optimization of Radiation Protection in Operations

(160) The level of radiation protection for an operation partly depends upon factors that are also relevant to the design; e.g. the positioning of the radiation-emitting equipment, the pathways to be followed by personnel, and the design-basis radiation and contamination levels. No clear-cut distinction can be made in this respect between design and operation. Generally, these factors are already fixed when the design is performed and this can introduce some constraints on the possibility of optimizing radiation protection at the operation stage. However, the collective exposure and the associated radiation detriment resulting from a given operation can still be very different according to the way in which the operation is carried out, the number and competence of the personnel involved, the type of personnel protective equipment, the choice of tools (manually or remotely operated), the quality of management and operational instructions, and other factors. It is difficult to predict, in quantitative terms, the influence of these last factors upon the variation of the radiation protection level. For these

reasons, the radiation protection associated with an operation is less amenable to optimization than at the design stage, being much more influenced by human factors which can be difficult to quantify.

(161) The assessment of the differential cost involved in a variation of the radiation protection level associated with an operation is made particularly difficult by the existence of the above-mentioned human factors. In fact, all the above parameters are modified when a given operational procedure is changed to an alternative corresponding to a different level of radiation protection, but their contributions to the resulting change in operating costs are, in some cases, difficult to determine. These include the cost of manpower in relation to type and competence of the personnel employed, the cost of monitoring and control, the costs induced by working accidents and other disturbances of the working practices. Similar difficulties are encountered in the assessment of the differential detriments.

(162) In conclusion, the quantification of costs and detriments and the consequent optimization process in operations can seldom be complete, a situation that renders decisions about alternative operational procedures largely qualitative and intuitive, with a substantial content of non-quantitative value judgment.[14] This limitation is rarely experienced in the optimization of design. In any event, in several practical cases quantitative values can be assessed approximately or in ranges and this is often sufficient for operational radiation protection purposes.[15] There are situations, however, where factual judgments are possible even though value judgments are also involved. This may be the case with medical radiodiagnosis, where the principle of optimization in operational practice can be widespread (see paras. 179 *et seq.*).

(163) Notwithstanding the above considerations, some examples of the optimization process for different types of operations are also included in this report. For the reasons given, the examples are only intended to identify conceptually the main problems associated with optimization in operations rather than to develop model problems framed to illustrate a rule. The precautions indicated in para. 125 are also applicable to the examples of optimization of operations.

(164) The term operation can be used with different connotations. Operations range from a whole set of homogeneous actions involving radiation exposure in a country for an indefinite period of time, to a single action or a sequence of actions in a specific plant for a limited period of time. Applying the process of optimization to the selection of levels of radiation protection in such a spectrum of operations would require a case-by-case approach, and it may be helpful, for the purpose of this section, to group different types of similar operations.

(165) The first group of operations includes the whole range of activities carried out in the frame of a given practice characterized by a wide distribution of radiation sources at the national or regional level. Even if these practices have already been subjected to the justification process, their implementation might still require optimization of radiation protection. Examples of these operations are the transport of radioactive materials, the medical uses of radiation and radionuclides and the use of consumer products containing radioactive materials, including natural radioactivity (e.g. natural gas or building materials). For their implementation, the activities embraced by these operations may well require the design and construction of specific installations or equipment. However, the overall optimization of the whole operation is subsequent to, and can be assumed not to interfere with, optimization of radiation protection in these specific installations or equipment. Optimization of radiation protection for these operations might be performed at national or regional level, involving a number of different parties, from governmental authorities to operators.

(166) A narrower meaning of the concept of operation is that applied to the operational phase

of a single installation, after the planning, design and construction stages have been completed. Typical examples are the operation of a nuclear installation or the use of a given x-ray machine or radiation source by an industrial plant or a hospital. Radiation protection in the installation is assumed to have already been optimized at the planning, design and construction phases; however, there usually remains an ample margin for changes in operations and procedures which justify and require a further optimization. Optimization will usually be carried out at the level of the individual installation and involves only the operational management and the radiation protection staff. In some cases a higher level of management will be involved in decision-making when particularly high expenditure is likely to be incurred or when the results of optimization for a given installation are to be extended to similar installations. The relevance of human factors in the planning of this type of operation may make the formal optimization procedure difficult to be performed. However, at least intuitive optimization should be considered.

(167) A further group of operations includes individual working actions or activities having a specific objective in the context of broader-scope operations and being more limited in scope and time. Examples are a maintenance or repair operation of a given equipment unit, an in-service inspection in a nuclear installation, an individual medical diagnostic examination or radiotherapeutical treatment, or a single research experiment involving exposure to radiation.

(168) A special type of operation is that experienced in unforeseen malfunctions and accidents which cannot be considered as minor mishaps expected in normal operation. Typical examples are the emergency countermeasures taken in the event of a nuclear accident. In this case optimization depends on local circumstances at the time of the incident but preliminary planning can be done in advance on a contingency basis.[19] Human and social factors can play a special role in this case and make it difficult to apply the optimization process in a formal and quantitative way.

(169) Some types of operations, identified in the previous paragraphs, will be analysed and examples of optimization of the involved radiation protection will be discussed. The examples are basically aimed at conceptually identifying the main parameters involved in the optimization process. It is not expected that they be adopted, as such, as models for resolving practical cases of optimization of operations.

Examples of Optimization of Radiation Protection in the Transportation of Radioactive Materials by Road, Rail and Waterways

(170) The transportation of radioactive materials involves regular movements of materials associated with the nuclear fuel cycle (fissile material, fresh reactor fuel, spent reactor fuel, radioactive wastes) and with various applications of radionuclides and radiation sources in research, industry and medicine. This process takes place over a network of pathways connecting places where such materials are produced and used. Each movement between two of the above points involves a radiation risk to the workers involved and to the population living along the transport pathway, as a result of exposure in normal conditions of transport and of possible exposure in the event of an accident leading to a release of radioactive material. A theoretical example of optimization, aimed at dealing only with routing of radioactive materials, will be discussed. It should be noted, however, that the most effective contribution from optimization might be found in its application to the standard design of containers for relatively small radioactive sources.

(171) The potential exposure associated with transportation accidents, as well as the actual exposure in normal transport conditions, can be estimated in terms of detriment. The consideration of accidental exposures and their detriment is beyond the scope of this report,

particularly as far as low-probability accidents involving high doses are concerned;[7] however, this type of consideration could override optimization of radiation protection. In any case, the protection needed to avoid or mitigate more probable minor accidents leading to low level exposures to radiation might be formally optimized. If so, the attention should be focused not only on the detriment associated with normal transport operations but also on that resulting from minor accidents during transport.

(172) In order to assess the detriment to the population due to a given transport operation, it would be necessary: (a) to determine the corresponding source term, including type and amount of radioactive material being transported, features of transport packages, radiation exposure rate as a function of distance within and around the transport vehicle, likely minor accidental releases (and their probabilities); (b) to develop a dosimetric model allowing for the calculation of the distribution of dose equivalent to individuals at various locations along the transport pathway (this will depend on the radiation exposure rate around the vehicle, the speed of the vehicle, the physical features of the pathway and other factors); and (c) to apply the above model to the actual distribution of population within a given distance from the road, rail or waterway in order to calculate the collective dose commitment associated with the given transport operation along the particular pathway. This should include the contribution from the exposure of the transport operators, and should apply to normal transport conditions as well as to minor accidents.[2]

(173) The calculation can conceptually be extended to an entire network of transport pathways connecting the points of production and use of radioactive materials. Thus, the total detriment associated with the full system of radioactive material transport in the country can theoretically be evaluated. Generally, the transportation between any two points in the system may be achieved through different alternative pathways of transport (air, road, rail or waterway) with which different values of radiation detriment are generally associated owing to the different features of the transport (packaging standards, speed, pathway characteristics) and the different distribution of population. These alternatives generally imply differences in the transport costs due to the different lengths of the alternative pathways, as well as to the type of transport means and the pathway features. If the detriment and the cost associated with each alternative transport network and system considered could be formulated, a theoretical optimization can be performed using the methods described in Section B.

(174) The above example illustrates a particular case in which the optimization of protection is unlikely to be a significant factor in the planning of transport operations, as distinct from the design of packaging. Other factors, e.g. physical security, could play an important part in planning the operations themselves. The example, nevertheless, sets out the principles for the application of the optimization concept.

Examples of Optimization of Radiation Protection in Medical Uses of Radiation

(175) Conceptually, optimization of radiation protection also applies to the reduction of exposures of patients who undergo a radiological examination or treatment. However, a number of practical difficulties arise. First, it is often difficult to reduce unnecessary exposures without influencing the intended useful exposure of the patient and therefore also the clinical result. Secondly, the use of the (collective) effective dose equivalent as the basis for the assessment has a number of limitations if the age and sex distribution of the exposed group of patients, or their life expectancy, differ substantially from the assumed characteristics of the normal population for which the ICRP organ weighting factors have been derived.

(176) The first difficulty is the most important one. If optimization of radiation protection is not "pure", because the protective measures influence the clinical result, the consideration

becomes a mixture of justification of alternative solutions and optimization of various elements of protection. Optimization of protection turns into "optimization" in a wider sense. For instance, if alternative systems for radiodiagnosis, giving different radiation doses, are available at different costs, balancing changes in costs and detriments is not enough for deciding which system provides an optimum level of radiation protection. Rather, several other considerations should be made as follows: (i) the possible decreased accuracy of the radiological procedure which will involve alteration in "trues" and "falses", both "positives" and "negatives"; (ii) the change from one system to another may entail modifications to other risks derived from the alternative procedure; (iii) the "optimized" system may be more difficult to use and results, in the end, in higher doses (e.g. if a protection system makes fluoroscopy clumsy or if it introduces poorly visible images, a longer fluoroscopy time may be required); (iv) a higher dose per patient, even at the same protection cost, might not necessarily be worse, since it may allow for more patients to receive the benefit of radiation (e.g. if an isolated nuclear medicine service does not have enough scanners, it may be worthwhile to use higher doses of radioisotope per patient so as to submit a larger number of patients to the necessary studies).

(177) Furthermore, there are several typical factors affecting benefits and detriments arising from the medical use of radiation and that are hard to quantify. The values of either the life saved or of the time of illness decreased in a patient is a benefit which might not be quantifiable through the approaches presented in paras. 90 *et seq.* In fact, these methods of valuation are applicable to statistical lives rather than to the life of a given individual. A radiological examination may benefit the patient by avoiding his submission to other diagnostic studies; this induced benefit is another factor difficult to measure due to the uncertainties involved in the expected detriment from the other studies. A good use of radiation may introduce additional benefits to public health, such as the detection of contagious diseases and a shortened hospitalization, and these are factors that are hard to take into account. Furthermore, there are benefits, such as the value of pain-suffering saved when an operation is avoided, or the extent to which knowledge of not having a serious disease benefits an individual, which are basically subjective and probably unquantifiable. Several other factors affecting the detriment depend on the characteristics of the patients and are also difficult to quantify; e.g. detriment in children versus that in old patients, and detriment in a healthy patient versus that in a patient carrying an incurable disease.

(178) In spite of the problems presented in the above paragraphs, some stylized examples and a discussion are presented below on the use of cost–benefit techniques in optimization of radiation protection in radiodiagnosis, radiotherapy and nuclear medicine. This material is intended for purposes of illustration only, since it appears that optimization in medicine should be constrained to intuitive decisions rather than to quantitative formal procedures.

Radiodiagnosis

(179) Exposures to radiation from medical diagnosis using x rays and other ionizing radiations have received particular attention as contributors to the collective dose.[17,18,26,27,36,72] In fact, medical radiodiagnosis is probably the main contributor to the collective dose from man-made sources. Therefore, optimization of radiation protection in medical radiology could lead to significant reductions in the overall radiological impact. Optimization can conceptually be applied to the whole process in medical radiology, from the original request for an examination to the final reporting of the films.

(180) As an example of the application of the optimization concept in medical diagnosis, consideration may be given to the installation of rare-earth screens in x-ray installations. It may be reasonable to assume that, in a standard x-ray service, a major fraction of the

examinations could be performed with rare-earth screens. This means that also a major fraction of the total collective dose currently incurred is liable to be reduced. It may be assumed that the collective dose saving may be up to the order of 2/3 of that total. The costs of each rare-earth screen and its lifetime is fairly well known; thus, the total crude cost could be easily estimated. If this assessment were made with current figures, the quotient $\Delta X/\Delta S$ would approximately be of a few tens of US$ per man sievert in terms of skin dose equivalent (in terms of effective dose equivalent, the quotient should be rather higher). These quotients compare well with the figures of α being used by some national authorities and indicate that application of the optimization process would be worthwhile.[8] It should be mentioned, however, that different image qualities could result in different qualities of diagnosis; this is a relevant factor to be considered in a final decision.

(181) Another example is the optimization of a quality control programme to reduce the number of rejected diagnostic x-ray films. Reject rates in x-ray departments vary considerably, from a few per cent to some tens of per cent. If quality control measures decrease this rejection rate, then it is possible to save a considerable fraction of the total collective dose presently incurred.[22] The associated cost could be quite low, involving a quality control scheme to achieve a reduction in rejected films (trying to identify the weak areas in the work pattern), checking of generator output by simple tests, processor checking by means of film exposed in a sensitometer and possibly by other means. However, any further testing will usually require the services of a good physicist, whose cost and availability would cause this programme to be carried out only occasionally, perhaps once or twice a year. The other forms of quality control mentioned above can be carried out by the ordinary departmental staff on a daily or weekly basis. However, it must be emphasized that, although the repeat rate can be improved by quality control, it is also dependent on the accuracy desired. If more substandard films are accepted, there is a greater risk of missing a diagnosis; thus, a sort of subjective optimization may be needed in deciding which film to repeat.

Radiotherapy

(182) The radiation protection of patients undergoing radiotherapy is also subject to the optimization requirement; but the use of optimization techniques in this field might present more particular problems. The principle giving the general framework is, in this case, the same as in other practices. The methods for applying this principle, however, are rather different and necessarily more complicated than those discussed before. On the one hand, the patient being treated might suffer inevitable non-stochastic effects. The value of the collective dose, therefore, would not provide a measure of the objective health detriment because the severity of the effects will, in this case, be dependent on the dose. On the other hand, the concept of effective dose equivalent itself is not applicable to these particular cases of high exposure. The development of a methodology for applying the principle of optimization to radiotherapy therefore needs further research. Examples of optimization of radiation protection in radiotherapeutic practices have not been attempted within the limited framework of this report.

Nuclear medicine

(183) Other examples of optimization in medical operations can be found in the use of radiation sources and radioactive substances in nuclear medicine. The radiation detriment associated with the operation of a medical diagnostic unit using radionuclides clearly depends upon the number of persons (patients and personnel) involved. Moreover, to a considerable extent, it also depends on the types of radionuclides used, on the doses administered and on the

quality (particularly the sensitivity) of the instruments adopted for measuring radiation. In particular, the use of short instead of long half-life radionuclides can decrease the *per caput* dose equivalent to patients and, consequently, radiation detriment, but it might increase the exposure and detriment of the workers. On the other hand, using detection and measurement instrumentation of higher sensitivity means that a lower radioisotope dosage can be administered for the same diagnostic information, with a resulting decrease in detriment to the public and workers. These parameters can be combined in an optimization process. It is possible to balance the cost involved in adopting different types of radionuclides (with different half-lives and emitted radiation spectra) and different types of measuring apparatus (with different sensitivities and accuracies) against the corresponding costs of radiation detriment. An example of optimization of radiation protection in nuclear medicine operations is discussed in Appendix G.

Examples of Optimization of Radiation Protection in the Use of Consumer Products

(184) In many countries, practices have been or are being introduced involving the use by the general public of consumer products containing small quantities of radioactive materials (man-made or natural). These practices should be authorized by the competent authorities on the basis of a review of their justification.[50,55]* Notwithstanding, many of the practices, even if they involve low levels of exposure, may require optimization of protection. It should be noted, however, that, if the expected collective dose commitment were very low, care should be taken when applying optimization since the cost of the process itself could be more expensive than the gain achieved.

(185) In some cases, the optimization procedure appears to be relatively straightforward. A conceptually simple example is that of the domestic use of natural gas containing radioactive materials. In this case it is possible to estimate the detriment in terms of collective dose arising from exposure of the users to radioactive contaminants in the combustion products.[3,37] For this purpose it is necessary to determine the source term including the production rate of natural gas, its radioactive material content and its consumption rate for the different types of uses (either industrial or domestic). Then it is necessary to make appropriate assumptions concerning the habits of the population in using this gas and the mechanisms of release and behaviour of radionuclides. On this basis a model can be developed describing the pathways and mechanisms for the radiation exposure of people and an average individual dose equivalent can be calculated per unit gas consumption rate and radionuclide content. If the source term data and the data concerning the number and distribution of people involved are applied to that average, it is possible to assess the relevant collective dose and the associated health detriment. Keeping all the conditions of use unchanged, the level of individual and collective exposure is essentially controlled by the gas activity content at the points of use. This can probably be varied to a wide extent by the use of various systems of gas purification at the production site or in the distribution network, thus giving rise to possible different levels of radiation exposure and detriment, which can be easily assessed. The cost associated with the various gas purification systems can also be estimated. Therefore, the optimization process can be applied and the determination of an optimized balance between the costs associated with different levels of radiation protection and the corresponding detriment levels appears straightforward. Appendix H presents the algebraic formulation of an example of optimization of protection in the domestic use of natural gas.

* See also International Commission on Radiological Protection. Principles for limiting exposure of the public to natural sources of radiation. A report of Committee 4 of ICRP. (In preparation.)

(186) A more complex case is the practice of using building materials containing natural radioactive material in artificially enhanced concentrations. It seems appropriate to envisage a process of optimization in the building industry aimed at reducing the detriment incurred by the people from exposure to building materials during construction and in habitation of dwellings.[14,15] Consideration should be given to different national strategies for selecting building materials, taking into account the distribution of natural building materials throughout the country, the sources of raw materials used by industries manufacturing (artificial) building materials (including by-products from the chemical industry), the costs of extracting and transporting materials with different activity contents, including the cost of harm due to working accidents, and so on. The total cost associated with each strategy could be calculated as could the corresponding detriment. However, it would probably be difficult to calculate the optimized balance between the different options by using only the simple cost–benefit analysis presented in this report, due to the substantial effect of several other considerations which can be handled only on the basis of a value judgment. These include, for example, the social and economical implications of moving job sites from one part of the country to another and of directing the industry to select or reject given sources of raw materials, and the public health problems of deliberately inducing different levels of detriment within different sectors of the population depending on whether they live in newly-built or old houses. Such factors are difficult to quantify in monetary terms in the context of the optimization methodology. Moreover, this case could be further complicated by the fact that the cost of production might not be assumed as independent from either radiation protection costs or detriment costs.

Examples of Optimization of Radiation Protection in Nuclear Power Plant Operations

(187) The most general and complex case of optimization of radiation protection during the operational phase of an installation is probably that related to the operation of a large nuclear installation, such as a nuclear power plant. In this case, the operational features which can be influenced in terms of optimization include: reactor fuel quality and management strategy, plant chemistry and decontamination procedures and practices, plant maintenance and inspection policy and procedures, personnel skill and training practices, policies on personnel rotation and the use of protective clothing, the extent to which remote handling tools and mock-ups are used, the extent of monitoring resources and health physics surveillance, and many others. Modifications of any of the parameters associated with these features can change the exposure of workers or of the population. Usually, a change in any of them also implies a change in economic cost. It would, therefore, appear feasible to calculate an optimized balance for each of the relevant parameters (if they are independent of each other), or for each appropriate combination of mutually dependent parameters. Unfortunately, many of these operational parameters are based essentially on factors (human or otherwise) that are difficult to quantify in technical or economic terms. Hence, they introduce a degree of uncertainty and lack of definition into the optimization process which can be overcome, in decision-making terms, only by qualitative value judgment. Moreover, it is in nuclear power plant operations where the problem of deciding whether reducing individual doses at the expense of some increase in collective dose does usually apply. As presented in this report, the dose limit applies a step function constraint on optimization. Therefore, providing that individual doses are below the limits, the best option should always be that delivering the lowest collective dose for a given cost of protection. However, as individual doses approach the dose limit, an additional component of the detriment, other than the objective health detriment, might be considered, the cost of which should be added to the cost of the objective health detriment (see para. 87).

(188) The exposure of personnel in a nuclear power plant is influenced by many variables, including the ability of fuel elements to retain fission products, the extent of deposition of active corrosion products throughout the primary and auxiliary coolant systems, the reliability of other specific equipment and the station layout.[54] A major part of this exposure is received during maintenance, waste handling, in-service inspection, refuelling and non-routine operations (such as repairs and modifications). Active corrosion products are the major source of radiation in connection with these operations in water-cooled reactors. Thus, it is possible to reduce substantially the exposure of plant personnel by minimizing the formation of corrosion products and their deposition in the plant circuits. Great improvements can clearly be obtained by proper design, but good results are also achieved by continuously monitoring and adjusting oxygen concentration and pH in the primary coolant, by periodic chemical decontamination of major serviceable components and by draining and flushing the systems prior to operations such as maintenance or replacement of equipment.[54]

(189) It is possible to calculate the cost of improving operational procedures, by developing better methods of decontamination, and draining, flushing and decontaminating circuits. The decrease in radiation detriment brought about by these improvements can also be estimated, and it is therefore possible to apply optimization. Similarly, the strategy for managing fuel quality can be subject to the optimization process.

(190) There are areas where human and other intangible factors play a more or less important role, making optimization more complex. Examples of some of these factors have been included in para. 187. Changing each one of these would result in a change in the radiation detriment. However, there is a complex relationship between work performance, procedural controls and workers' exposure and little has been done so far to quantify these relationships. They will make a significant contribution to the overall optimization of radiation protection.

(191) The strategy for maintenance and in-service inspection of equipment, in terms of frequency, duration, depth, tools (e.g. use of remote handling or inspection tools) has a direct bearing on the exposure of the personnel to radiation. Less frequent or less detailed maintenance or inspections naturally lead to lower detriment levels. In this case, other considerations might have to be taken into account; e.g. a proper balance between the requirements of nuclear safety (which requires far more thorough maintenance and inspection work) and those of radiation protection (which would benefit from the opposite situation). However, if the required safety level is fixed, the optimization will be effected more simply between the costs of different possible maintenance and inspection strategies and the corresponding detriment. The costs involved in the definition of the different strategies may relate to the types of remote handling tools and the extent to which they are used, the manpower involved in the various operations in relation to their duration and the skill of the personnel required, the types and extent of use of individual protective systems and clothing, the degree and type of monitoring and health physics coverage and the personnel decontamination required.

(192) This optimization process is particularly complex because the above parameters have different effects on the costs and detriments, being at the same time closely interlinked and interactive. For example, the use of protective clothing, including breathing apparatus, lowers the performance of the wearers by lengthening the time necessary to complete a task and reducing mobility and dexterity (which also has a safety implication). Although the protective clothing reduces the intake of activity into the body, the dose from external radiation is increased as a result of the longer working time.[42] The use of protective clothing, therefore, cannot be optimized *per se* against the internal contamination levels corresponding to some alternative maintenance and inspection strategies, but it is necessary to find out a more

elaborate balance between the internal and external exposure and the various alternative strategies. This balance between internal and external exposure requirements varies from case to case depending on some of the other parameters involved in maintenance and inspection, e.g. the type of operations and the radiation and contamination levels present.

(193) Another aspect, which contributes to the complexity of the optimization process, is the possible need to use additional personnel, besides the permanent staff, on a shift basis to carry out particular operations in maintenance or repair. In this case the differential cost–benefit analysis could be hampered by a certain difficulty in determining the additional detriment expected from the additional staff. The inefficiency of using large numbers of individuals, over short periods of time, to accomplish a single task could have a negative influence on the radiation detriment which is difficult to estimate.[20,71] The extra staff cost, on the other hand, will be affected by considerations such as the trade and skill level required, the availability and location of suitable personnel and the useful employment of staff who have already received their planned radiation exposure.[42]

(194) From the above examples it can be seen that optimizing radiation protection in the operation of a large nuclear installation can be a particularly difficult task. On the other hand, it is a worthwhile challenge because of its significant potential for improving radiation protection, and there is a good case for carrying it through, except for a few cases in which the occupational exposure involves such a low collective dose commitment that there is really no justification for spending any money on limitation of exposure.[15] In any event, to optimize radiation protection during operations it is necessary to assemble an adequate data base, including operating experience and economic information, from which the criteria for optimizing the control exposure might be derived in quantitative terms. For the time being, optimization in nuclear installations rests essentially on good engineering judgment on a case-by-case basis and tends to take the form of qualitative guidance (e.g. goals, objectives and statements of good practice), although some attempts towards more quantitative approaches have recently been reported.[20]

Examples of Optimization of Radiation Protection in Individual Operations

(195) As stated in para. 167, a given type of operation involves individual actions having limited objectives, scopes and duration, which are carried out within the framework of broader scope operations. The usual practice followed by radiation protection officers and operations management to keep exposures as low as reasonably achievable includes a number of aspects and logical approaches of what resembles an optimization process, but which cannot be defined as a quantitative optimization. The practice generally applied is in fact to identify and appraise the contrasting parameters involved in a given planned operation, and to try to strike a balance between them on the basis of qualitative judgment. Intuitive aspects play a relevant role for optimization of radiation protection in individual operations.

(196) A full quantitative optimization process would, by contrast, require the application of the whole procedure described in Section B of this report. A typical example is, again, an individual in-service inspection, maintenance or repair operation in a nuclear installation. There are many and diverse parameters capable of influencing exposure to radiation and, therefore, they require quantification if the planned operation is to be optimized. As a basis for planning the operation, it might be necessary to do preliminary surveys so as to obtain information about radiation fields, surface and air contamination and physical and mechanical problems that might be met during the operation. This survey would imply, in addition to economic cost, a radiation detriment due to exposure of the personnel doing the surveys, but also a successive saving in radiation detriment as a result of reduced exposure of the personnel involved in the proper operation. The existing radiation levels can frequently be reduced by

prior draining, flushing or other decontamination methods or by dismantling components and transporting them for service in a zone of lower radiation.[54] Again, these preparatory actions involve an economic cost and a radiation detriment cost, but these are counteracted by a saving in radiation detriment in the subsequent conduct of the operation. Optimization requires a careful balance of the above contrasting contributions.

(197) Training of personnel for the specific operation and selecting personnel with adequate skill and experience involve essentially an economic cost, but could give rise to a saving in health detriment. In this context, a specific aspect to be evaluated is the introduction of dummy runs on mock-up equipment; this can be useful not only for training personnel but also for identifying problems that could be encountered in the real situation, and selecting or preparing special tools and procedures to reduce potential exposure of personnel. The provision of portable or temporary radiation shielding, ventilation systems, containment and enclosures and expendable floor coverings can reduce external exposure and the internal irradiation of personnel during the operation, but do, of course, involve a cost to be accounted. The rotation of personnel to keep individual doses below certain limits usually increases the collective dose and is another relevant parameter, as already discussed with reference to operations in nuclear installations.[54]

(198) The above list of possible relevant parameters is not exhaustive and several other factors might have to be evaluated in terms of cost and detriment, on a case-by-case basis, depending on the specific operation under examination. Some of the above parameters present difficulties of quantification (in terms of cost or in terms of effect on the radiation detriment), and several mutually interact (impeding or hindering any step-by-step optimization involving only one parameter for each step of the process). Finally, some of them can affect not only radiation protection but also the plant availability (e.g. the necessary duration of a plant outage can depend on the procedures adopted for preparing and executing the operation having regard to personnel radiation protection optimization). This last possibility would further complicate optimization, because the production cost, P, would not be constant but would depend upon the radiation protection level selected.

APPENDIX A

Algebraic Example of Optimization of Radiation Protection by the Design of a Simple Planar Shield for a Source of Radiation

(A-1) An example of optimized design of a simple planar shield is presented. For the purpose of the example, it will be assumed that the effective dose-equivalent rate, $\dot{H}_E$, at a point on the external face of a simple planar shield is, approximately,

$$\dot{H}_E = \dot{H}_u \, e^{-\Gamma w}$$

where $\dot{H}_u$ is the maximum effective dose-equivalent rate, which would be incurred by a hypothetical receptor located in contact with the external face of an initial minimum thickness shield (in practical shielding design, $\dot{H}_u$ can be taken to be the maximum dose-equivalent rate at the point of occupancy being considered outside the shielding)—in any case $\dot{H}_u \leq \dot{H}_L$;

Γ is the effective attenuation coefficient (which includes the effects of build-up);

w is the thickness of the extra shield; and, therefore,

$e^{-\Gamma w}$ is the dose reduction factor of the extra shield.

(A-2) Since a constant ratio, ρ, between average and maximum individual doses has also been assumed (see para. 129), the average effective dose-equivalent rate incurred by the exposed people will be:

$$\bar{\dot{H}}_E = \rho \dot{H}_u \, e^{-\Gamma w}$$

(A-3) Assuming that the lifetime of the shield in the example is τ and that N persons will be exposed in the radiation field during a fraction of time f_t (occupancy time factor), the collective dose can be represented by the following equation:

$$S_E = N f_t \tau \bar{\dot{H}}_E = N f_t \tau \rho \dot{H}_u \, e^{-\Gamma w}$$

The function of the cost of detriment, $Y = Y(w)$, can, therefore, be formalized as follows:

$$Y(w) = \alpha N f_t \tau \rho \dot{H}_u \, e^{-\Gamma w}$$

(A-4) Further, assuming that the shield in the example is rectangular, the function of the cost of protection, $X = X(w)$, (cost of the shield as a function of thickness) is (see para. 132):

$$X(w) = X_S = X_V h l w + X_I$$

where X_V is the cost per unit volume of shielding material installed;

h is the shield height;

l is the shield length;

w is the shield thickness; and

X_I is the cost of the support installation, which, for the purpose of this example, is assumed to be constant with thickness within a small range of thickness variation.

(A-5) The objective function of the example results from the sum of the cost equations:

$$U = X(w) + Y(w) = X_V h l w + X_I + \alpha N f_t \tau \rho \dot{H}_u \, e^{-\Gamma w}$$

(A-6) In order to obtain the optimum shield thickness, w_o, the objective function must be minimized with respect to w. As presented in Section B, this can be done by differentiating the objective function with respect to w and equating to zero. Thus,

$$X_V h l - \alpha N f_1 \tau \rho \dot{H}_u \Gamma \, e^{-\Gamma w_o} = 0$$

(A-7) In the example presented, the optimized dose reduction factor, $e^{-\Gamma w_o}$, can be derived from the equation of para. A-6:

$$e^{-\Gamma w_o} = \frac{X_V h l}{\alpha N f_t \tau \rho \dot{H}_u \Gamma}$$

The optimized shield thickness will be equal to the sum of the initial thickness plus the extra thickness resulting from the above optimized dose reduction factor. Annex A_1 presents a numerical example where the algebraical procedure described above has been applied to a specific situation.

(A-8) A more formalistic treatment of the above example can be made by extending the example to cases where several groups of people with different occupational time factors are exposed and where the dose build-up factor is not a simple exponential function of the shield thickness. In this case, the collective dose can be described by:

$$S_E = \sum N_j f_{t_j} \tau \rho_j \dot{H}_u B(\mu w) \, e^{-\mu w}$$

where $\dot{H}_u$ is the maximum effective dose-equivalent rate, which would be incurred by a hypothetical receptor located in contact with the external face of an initial minimum thickness shield (in practical shielding design, $\dot{H}_u$ can be taken to be the maximum dose-equivalent rate at the point of occupancy being considered outside the shielding)—in any case, ($\dot{H}_u \leq \dot{H}_L$);

$B(\mu w)$ is the shielding dose build-up factor;

μ is the dose attenuation coefficient;

w is the thickness of the extra shield;

$\dot{H}_u B(\mu w)\,\mathrm{e}^{-\mu w}$ is, therefore, the maximum effective dose-equivalent rate against the face of the extra shield;

ρ_j is the ratio between the average effective dose-equivalent rate, to which individuals in a group j of people are exposed, and the maximum effective dose-equivalent rate;

τ is the lifetime of the installation;

f_{t_j} is the occupancy time factor of a group j of exposed people; it denotes the fraction of time during which individuals in group j are exposed to radiation from the source;

$f_{t_j}\tau\rho_j\dot{H}_u B(\mu w)\,\mathrm{e}^{-\mu w}$ therefore represents the average effective dose equivalent incurred by members of the group j as a result of the introduction of the extra shield; and

N_j is the number of people in the group j.

(A-9) The objective function can then be formalized as:

$$U = \alpha\dot{H}_u B(\mu w)\,\mathrm{e}^{-\mu w}\tau \sum_j N_j f_{t_j}\rho_j + X_V h l w$$

which should be minimized with respect to thickness.

(A-10) The optimum thickness can be determined by differentiating the objective function with respect to w and setting it equal to zero:

$$\alpha\dot{H}_u\tau \sum_j N_j f_{t_j}\rho_j\,\mathrm{e}^{-\mu w}\left(\frac{\mathrm{d}B(\mu w)}{\mathrm{d}w} - \mu B(\mu w)\right) + X_V h l = 0$$

Therefore, the optimum dose reduction factor of a simple wall-type shielding of a selected material will be obtained when:

$$\mathrm{e}^{-\mu w_o} = -\frac{X_V h l}{\alpha\dot{H}_u\tau \sum_j N_j f_{t_j}\rho_j\left(\dfrac{\mathrm{d}B(\mu w_o)}{\mathrm{d}w_o} - \mu B(\mu w_o)\right)}$$

The above equation provides a solution for a value of w, assessing the optimum extra thickness, w_o, that is to be added to the initial shield thickness.

(A-11) It could also have been assumed that the individual dose distribution varies through the optimization process. This might occur if the shield thickness could change substantially as a result of optimization, thus modifying operational parameters as a result of different working practices through a thicker or thinner shield. The problem could conceptually be solved by assuming that the ratio, ρ, between average and maximum dose rates will be a function of the shield thickness, w. In that case, the objective function introduced in para. A-9 will be as follows:

$$U=\alpha\dot{H}_u B(\mu w)\,e^{-\mu w}\tau\sum_j N_j f_{t_j}\rho_j(w)+X_V hlw$$

Therefore, the optimum dose reduction factor will be :

$$e^{-\mu w_o}=-\frac{X_V hl}{\alpha\dot{H}_u\tau\sum_j N_j f_{t_j}\left(B(\mu w_o)\frac{\partial\rho(w_o)}{\partial w_o}+\rho(w_o)\frac{\partial B(\mu w_o)}{\partial w_o}-\rho(w_o)\mu B(\mu w_o)\right)_j}$$

ANNEX A_1

Numerical Example of Optimization of Radiation Protection by the Design of a Simple Shield

(A_1-1) A numerical example of optimization of a simple shield in a "hot" corridor of a laboratory is presented.[5] It is assumed that the shield material is standard concrete and that its installed cost is 100 \$ m^{-3}. The value of α is assumed to be 10^4 \$ (man Sv)$^{-1}$. The gamma-radiation energy is about 0.7 MeV, so that the effective attenuation coefficient is $\sim 14\ m^{-1}$. The value of ρ is assumed to be 10^{-1}. The total time of exposure (i.e. the lifetime of the installation times the occupancy factor) is taken to be 20 years. The number of people working is assumed to be one worker per 15 square meters of shield surface. The maximum effective dose-equivalent rate without extra shielding, $\dot{H}_u$, is taken to be 0.05 Sv y^{-1} (5 rem y^{-1}).

(A_1-2) Under the above assumption and using the expression in para. A-7, an optimum dose reduction factor can be obtained:

$$e^{-\Gamma w_o}=\frac{X_V}{\tau\alpha\Gamma\dot{H}_u f_t\rho}\frac{hl}{N}$$

$$=\frac{10^2\ \$\ m^{-3}\ 15\ m^2\ man^{-1}}{10^4\ \$\ (man\ Sv)^{-1}\ 14\ m^{-1}\ 5\ 10^{-2}\ Sv\ y^{-1}\ 0.1\ 20\ y}$$

Thus,

$$e^{-\Gamma w_o}=0.1$$

Therefore, the optimized dose reduction factor becomes 10^{-1}. This means that in this example it is worthwhile, as a design objective, to reduce the limit dose rate (i.e. that ensuring compliance with the dose limits) by a factor of ten.

APPENDIX B

Algebraic Example of Optimization of Radiation Protection by the Design of a Simple, Non-specific, Ventilation System

(B-1) In a confined space of volume υ, which is ventilated at a flow rate Q and, where sources of radioactive materials are leaking into it at a constant rate $\dot{A}$, the differential equation describing the temporal behaviour of the concentration of airborne radioactive material $C(t)$, can be approximated as follows:

$$\frac{dC(t)}{dt}=\frac{\dot{A}}{\upsilon}-\left(\frac{Q}{\upsilon}+\lambda\right)C(t)$$

where Q is the flow rate continuously injected by the ventilation system; and

λ is the radioactive decay constant of the contaminating nuclide.

Thus, $C(t)$ will become:

$$C(t)=\frac{\dot{A}}{(Q+\lambda\upsilon)}\left(1-e^{-\frac{(Q+\lambda\upsilon)}{\upsilon}t}\right)+C(o)\,e^{-\frac{(Q+\lambda\upsilon)}{\upsilon}t}$$

where $C(o)$ is the initial concentration.

Usually, $Q \gg \lambda\upsilon$ and $C(o)=0$. On the other hand, for radiation protection purposes, it is sufficient to assess the equilibrium concentration $C \equiv C(\infty)$. Thus, it follows that,

$$C=\frac{\dot{A}}{Q}$$

(B-2) The collective dose commitment, S^c_E, incurred as a result of exposure to a contaminated and ventilated environment, can be expressed as follows:[20]

$$S^c_E=Nf_t\tau F_d C=Nf_t\tau F_d\frac{\dot{A}}{Q}$$

where N is the number of individuals in the group of exposed people;

τ is the lifetime of the installation;

f_t is the occupancy time factor;

F_d is a dosimetric factor converting activity concentration in dose rate (i.e. the effective dose-equivalent rate incurred by exposed individuals, per unit concentration of radioactive material in air), which is assumed to be an average value corresponding to the mean age of the exposed people;

The cost of detriment can therefore be formalized as follows:

$$Y=Y(Q)=\alpha Nf_t\tau F_d\frac{\dot{A}}{Q}$$

(B-3) Assuming that the total cost of ventilating can be reduced to operational cost only and that the assumptions made in paras. 143 and 144 apply, the cost of radiation protection will be:

$$X=X(Q)=abf\tau Q$$

where a and b are constants representing the cost of electricity per unit of electrical energy, and the energy expended to condition and circulate a unit volume of air, respectively; and

f is the fraction of time in which a system operates.

(B-4) Therefore, the objective function will be the following:

$$U=\alpha Nf_t\tau F_d\frac{\dot{A}}{Q}+abf\tau Q$$

To minimize the objective function, the above expression should de differentiated with respect to the ventilation flow rate and set equal to zero. Thus, if b is assumed to be independent of Q,

$$-\frac{\alpha N f_t \tau F_d \dot{A}}{Q^2} + abf\tau = 0$$

and the optimum flow rate, therefore, can be determined by the following equation:

$$Q_o = \left(\frac{\alpha}{ab} N F_d \dot{A}\right)^{1/2}$$

It is emphasized that the assumption of independence between b and Q should be used with caution (see para. 144). In some practical cases b will be a function of Q. In these cases, the exponent of the function defining Q_o would be lower than 1/2.

(B-5) The equation of para. (B-4) can be generalized, assuming that: (i) several radionuclides, i, are present in the air; (ii) they are released from several containments, k, at different rates, A_{ik}; and (iii) several groups of people, j, with a number of individuals, N_j, and an occupancy time factor, F_{t_j}, are exposed. The generalized equation will be as follows:

$$Q_o = \left(\frac{\alpha}{abf} \sum_j f_{t_j} N_j \sum_i F_{d_i} \sum_k \dot{A}_{ik}\right)^{1/2}$$

where f is a factor representing the fraction of time in which the ventilation system operates.

(B-6) Radiation protection in ventilated confinements can be achieved in two steps. First, the minimum limiting flow rate, Q_L, which should be able to keep the concentration of a given radionuclide in air below the relevant Derived Air Concentration (DAC) so as to ensure compliance with the dose limits, is determined; and, second, the flow rate can be increased, if necessary, to an optimum level, so as to ensure that doses are kept as low as reasonably achievable. The fractional increase of flow rate can be determined by the relation, r_Q, given by:

$$r_Q = \frac{Q_o}{Q_L}$$

(B-7) Using the equation shown in para. B-1, Q_L becomes:

$$Q_L = \frac{\dot{A}}{\mathrm{DAC}}$$

(B-8) Therefore, the relation r_Q for a given nuclide can be formalized as follows:

$$r_Q = \mathrm{DAC}\left(\frac{\alpha N F_d}{ab\dot{A}}\right)^{1/2}$$

ICRP Publication 30[32] recommends values of DAC for occupational exposure. Annex B_1 presents two numerical examples which use the above formulation.

ANNEX B_1

Two Numerical Examples of Optimization of Radiation Protection through Ventilation

(B_1-1) An example is presented which considers the ventilation system for a laboratory of a plant in which a few terabecquerel per annum of radiopharmaceuticals containing iodine-131 are processed. About 12 full-time workers are located in the ventilated laboratory. The iodine leak rate, $\dot{A}$, into the laboratory was 3.1 10^9 Bq y^{-1} (3.7 10^5 Bq h^{-1} or 10^{-5} Ci h^{-1}). The value of the constant α/ab is assumed to be 10^8 m^3 (man Sv)$^{-1}$ [10^6 m^3 (man rem)$^{-1}$] for this particular laboratory (i.e. $\alpha=10^4$ \$ (man Sv)$^{-1}$; $a=0.064$ \$ kW^{-1} h^{-1}; $b=5.2$ kW m^{-3} s). The dosimetric factor is $F_d=2$ 10^{-5} Sv y^{-1}/Bq m^{-3} (0.73 10^8 rem y^{-1}/Ci m^{-3}) and the Derived Air Concentration, DAC, for iodine-131 is 7 10^2 Bq m^{-3} (1.9 10^{-8} Ci m^{-3}).[32] Using the formulation shown in Appendix B, the fractional increase in flow rate r_Q, is given by:

$$r_Q=\mathrm{DAC}\left(\frac{\alpha N F_d}{ab\dot{A}}\right)^{1/2}$$

$$r_Q=7\ 10^2\ \mathrm{Bq\ m^{-3}}\left(\frac{10^8\ \mathrm{m^3\ (man\ Sv)^{-1}}\ 12\ \mathrm{man}\ 2\ 10^{-5}\ \mathrm{Sv\ m^3\ Bq^{-1}\ y^{-1}}}{3.1\ 10^9\ \mathrm{Bq\ y^{-1}}}\right)^{1/2}$$

$$r_Q\cong 2$$

which means that only a doubling of the minimum ventilation flow-rate is worthwhile.

(B_1-2) Another example is the ventilation of a room in a pressurized heavy-water reactor, where pipes conducting tritiated heavy water under high pressure are installed. The normal leak rate, $\dot{A}$, of tritium is about 3.1 10^{12} Bq y^{-1} (3.7 10^8 Bq h^{-1} or 10^{-2} Ci h^{-1}). The number of people in that environment can be variable depending on the operating conditions, but the average is about 10 full-time workers. The dosimetric factor for tritium (as water) is 6.3 10^{-8} Sv y^{-1}/Bq m^{-3} (2 10^5 rem y^{-1}/Ci m^{-3}) and the Derived Air Concentration, DAC, is 8 10^5 Bq m^{-3} (2.2 10^{-5} Ci m^{-3}).[32] The value of α/ab is taken to be 10^9 m^3 (man Sv)$^{-1}$ [10^7 m^3 (man rem)$^{-1}$] because of the lower value of the cost of electricity, in this case of own production, and due to the better efficiency of the blowers (i.e. $\alpha=10^4$ \$ (man Sv)$^{-1}$; $a=0.012$ \$/kW h; $b=2.9$ kW m^{-3} s). The value of r_Q is given by:

$$r_Q=\mathrm{DAC}\left(\frac{\alpha N F_d}{ab\dot{A}}\right)^{1/2}$$

$$r_Q=8\ 10^5\ \mathrm{Bq\ m^{-3}}\left(\frac{10^9\ \mathrm{m^3\ (man\ Sv)^{-1}}\ 10\ \mathrm{man}\ 6.3\ 10^{-8}\ \mathrm{Sv\ m^3\ Bq^{-1}\ y^{-1}}}{3.1\ 10^{12}\ \mathrm{Bq\ y^{-1}}}\right)^{1/2}$$

Thus,

$$r_Q\cong 11$$

In the above example, the results indicate that it would be worthwhile substantially to increase (by more than one order of magnitude) the minimum ventilation flow rate needed to comply with the dose limits.

(B_1-3) The two examples presented in this annex, in which actual values for the parameters are used, demonstrate that in some instances the optimization process can be readily applied to the performance of ventilation systems for confined locations where the potential for contamination by radionuclides exists. In these examples, the adjustment in ventilation performance necessary to achieve optimization was feasible. Indeed, ventilation is generally provided for the comfort of personnel or for reasons other than considerations of radiation protection and in many cases the ventilation rate will exceed that required for optimization purposes.

APPENDIX C

Variables Associated with Radon Contamination and their Influence on the Optimization Process

(C-1) Optimization assessments, when radon contamination is involved, require the use of special quantities related to this nuclide. These quantities and their interrelation are fully discussed in one of the Annexes to the 1982 Report of the United Nations Scientific Committee on the Effects of Atomic Radiation,[70] which studies exposures to radon, thoron and their decay products. This appendix presents a summary of the quantities which are relevant in relation to optimization assessments involving radon, including the related dosimetric aspect. The Appendix also discusses the uncertainties in the measurement of these quantities and their influence on optimization.

(C-2) As discussed in Appendix B, in cases of indoor air contamination the relevant protection parameter is the ventilation flow rate. The doses in these cases can be assessed on the basis of the remaining nuclide concentration in air. However, if the contaminant nuclide is radon, the relevant dosimetric quantity is not the *radon concentration* but the *potential alpha energy concentration of radon daughters*. Any of these interrelated quantities, as well as the radon daughter concentration, can be used in optimization assessments.

(C-3) The potential alpha-energy concentration of radon daughters in air is the sum of the potential alpha energy of all daughter atoms (i.e. the sum of total alpha energy emitted during the complete decay of each atom per unit volume of air). In some practical applications, the radon daughter concentration has been expressed in *working levels*, WL, and the exposure has been expressed as the integral of the concentration in air over the exposure time (e.g. expressed as working level months, WLM). WL was originally defined as any combination of short-lived radon daughters per litre of air that will result in the emission of $1.3\ 10^5$ MeV of alpha energy throughout their complete decay.

(C-4) Another relevant quantity is the equilibrium factor, F. The equilibrium factor is defined as the ratio of the total potential alpha energy for a given daughter concentration to that of the total potential alpha energy of the daughters in equilibrium with radon. The equilibrium factor can be expressed as

$$F = \Xi \frac{\varepsilon\alpha}{C_{Rn}}$$

where $\varepsilon\alpha$ is the potential alpha energy concentration (expressed for example in WL of radon daughters);

C_{Rn} is the radon activity concentration; and

Ξ is a dimensional constant.

The product FC_{Rn} is referred to as the equilibrium equivalent concentration of radon (EEC).

(C-5) The value of the equilibrium factor F for different rates of air changes can be calculated from the following formula, which is valid for a pure compartmental situation:

$$F = \frac{\frac{\lambda_A/v}{\lambda_A/v+1}\,A + \frac{\lambda_A/v}{\lambda_A/v+1}\,\frac{\lambda_B/v}{\lambda_B/v+1}\,B}{W} + \frac{\frac{\lambda_A/v}{\lambda_A/v+1}\,\frac{\lambda_B/v}{\lambda_B/v+1}\,\frac{\lambda_C/v}{\lambda_C/v+1}\,C}{W}$$

where λ_A, λ_B and λ_C are the decay constants of RaA, RaB and RaC, respectively;

ν is used as a pure rate of air changes, disregarding the wall effect;

A, B and C represent the potential α energy per unit activity of RaA, RaB and RaC, respectively; and

W is the potential α-energy content per unit activity of radon in equilibrium with its short-lived daughters ($W = \Xi^{-1}$).

(C-6) The F values can also be approximately represented by the following expression (where ν must be expressed in h^{-1}):

$$F(\nu) = 0.8\ e^{-0.75\,\nu} + 0.18 \quad \text{when} \quad \nu < 5\ h^{-1}$$

or by the linear expressions:

$$F(\nu) = -0.3\ \nu + 0.85 \quad \text{when} \quad 0.2\ h^{-1} < \nu < 1.5\ h^{-1}$$

$$F(\nu) = -0.08\ \nu + 0.55 \quad \text{when} \quad 1.5\ h^{-1} < \nu < 5\ h^{-1}$$

$$F(\nu) = -0.006\ \nu + 0.21 \quad \text{when} \quad 5\ h^{-1} < \nu < 30\ h^{-1}$$

$$F(\nu) = F_{30}\ e^{-0.019(\nu - 30)} \quad \text{when} \quad 30\ h^{-1} < \nu < 100\ h^{-1}$$

These approximate expressions are used in the example presented in Appendix D.

(C-7) The radon concentration in a confined space is proportional to the radon diffusion rate and inversely proportional to the ventilation rate. The concentration of daughters is influenced by the residence time of these daughters in the confined space and, thus, also depends on the ventilation rate. The F value can be determined on a theoretical basis taking these factors into account, but practical measurements have shown great variations from the calculated values.[69] If an average value of F is taken as 0.5 times the theoretical value based on ventilation only, the actual value of F will in most cases be within $\pm 50\%$ of the theoretical value. Therefore, in case of radon measurements, the corresponding actual radon daughter concentration can be estimated with an uncertainty of $\pm 50\%$.

(C-8) When backfitting a design for optimization purposes, there is always a need to know the current and expected situations. In case of radon daughter exposure, the concentration of radon daughters is determined by radon or radon daughter measurements. Both methods suffer from imperfections and an uncertainty of 10–20% is not unusual. Furthermore, there are diurnal and seasonal variations of the concentrations of up to one order of magnitude that can differ in adjacent locations in a building.[66,68] The determination of an actual average value of the radon and radon daughter concentration is, therefore, a difficult and time-consuming task and a few measurements may sometimes, at their best, provide an estimated average which deviates from the actual annual average by $\pm 50\%$.

(C-9) If radon, rather than radon-daughter, measurements are made, the estimation of the annual average concentration may be highly uncertain, probably 75%, unless measurements are repeated several times a year. The effective change of radon daughter concentration is estimated as the difference between two values based either on two sets of measurements or on one set of measurements and a calculated future value resulting from a change in ventilation. The relative error increases by these additional estimations. For instance, if the marginal protection cost per unit of saved collective dose commitment were say up to 2 times the recommended value, it might still be worthwhile to change the ventilation rate of a system ventilating radon. In this example, the saved collective dose commitment might in fact be much lower than estimated. An uncertainty of 75% means that the true value might be more than 4 times less than the estimated value and, therefore, the cost per unit of saved collective dose commitment could be 8 times higher than the recommended value. Accordingly, the region for dubious decision is a cost of 0.25–2 times the recommended value. This discussion can be summarized as follows:

—if $\Delta X/\Delta S > 2\ \alpha$, the action is not worthwhile (i.e. the result of the optimization assessment is negative);

—if $0.25\ \alpha < \Delta X/\Delta S < 2\ \alpha$, the action is dubious (there is a state of uncertainty); and

—if $\Delta X/\Delta S < 0.25\ \alpha$, the action is worthwhile (i.e. the result of the optimization assessment is positive).

(C-10) The uncertainties described above do not include inaccuracies associated with realistic (non-conservative) estimations of collective doses from radon exposures. If these are taken into account, even greater uncertainties would appear in optimization assessments involving radon problems. For instance, the aerosol size distribution and concentration in a closed environment influence the attachment of radon daughters to aerosols and, consequently, the uptake of the daughters in the human respiratory tract and the dose distribution. In optimization assessments which include sizeable increases in ventilation rates (e.g. in mines), there is often a significant change in the aerosol characteristics which can influence the exposure–dose relationship.

(C-11) The ICRP recommended an appropriate individual limit for occupational exposure to radon and its daughter nuclides.[35] The recommended annual limit for intake by inhalation, in terms of inhaled potential alpha energy, is 0.02 *J* in a year. The corresponding derived air concentration is then 0.3 WL. Although these limits are primarily intended to ensure compliance with the relevant dose limits, the derived occupational dosimetric factors could be provisionally used for optimization of ventilation systems controlling occupational exposures, in spite of their intrinsic conservatism.

(C-12) A derivation of dosimetric factors for members of the public under specific conditions have also been attempted under several assumptions. For instance, the breathing rate of the public is lower than that of workers in industrial plants. The uptake of radon daughters in the lung can be assumed to be similar in both cases. The occupancy on the other hand is different in houses than in normal working places. Taking all these factors into account, UNSCEAR reports approximate dosimetric factors for evaluating levels of exposure in members of the public.[70] These factors can provisionally be used in optimization assessments involving public exposure.

(C-13) The following are provisional dosimetric factors which could be used for assessing collective doses from radon exposure for optimization purposes:

Occupational exposure	$3.5\ 10^{-5}$ Sv y^{-1}/Bq m^{-3}
	(or $\sim 120\ 10^{-3}$ rem y^{-1}/pCi l^{-1})
	(or $\sim 120\ 10^{-3}$ Sv y^{-1} WL^{-1})
Exposure of members of the public (indoor)	$6\ 10^{-5}$ Sv y^{-1}/Bq m^{-3}
	(or $\sim 200\ 10^{-3}$ rem y^{-1}/pCi l^{-1})
Exposure of members of the public (outdoor)	$3\ 10^{-5}$ Sv y^{-1}/Bq m^{-3}
	(or $\sim 120\ 10^{-3}$ rem y^{-1}/pCi l^{-1})

These factors, which are derived from the ICRP limits for occupational exposure and from UNSCEAR, express the effective dose equivalent caused by 1 year's exposure to radon daughters, the activity of which is specified in units of equilibrium equivalent concentration (EEC) of radon.

APPENDIX D

Algebraic Examples of Optimization of Radiation Protection by the Design of Ventilation in Cases of Ambient Radon

(D-1) The collective dose commitment, S^c_E, in a limited number of individuals (N) exposed to the same radon daughter concentration is:

$$S^c_E = N F_d (\text{EEC}) \tau f_t$$

where F_d is the dose conversion factor for radon daughters (see Appendix C);

EEC is the equilibrium equivalent concentration of radon (see Appendix C);

τ is the lifetime of the installation; and

f_t is the relevant occupancy time factor.

(D-2) The EEC value has been expressed as the product of the radon concentration and the factor F (see para. C-4). As long as the ventilation rate is higher than 0.1 and the radon concentration in the inlet air is negligible, the radon concentration in a room varies approximately in inverse proportion to the rate of air changes or ventilation rate, v.

$$\text{EEC} = \frac{C_0 v_0}{v} F \kappa$$

where C_0 is the radon concentration at ventilation rate v_0;

F is the equilibrium factor, at the ventilation rate v; and

κ is a correction factor to take account of the various uncertainties related to the assessment of F (see Appendix C), which is assumed to be 0.5

(D-3) If the linear expression is used in the lower range of the ventilation rates, the expression for S^c_E will be (see paras. B-2 and C-6).

$$S^c_E = N F_d f_t C_0 v_0 \, 0.5 \left(\frac{0.85}{v} - 0.3 \right) \tau$$

(D-4) As indicated in paras. 143 *et seq.*, there are practical cases where the installation cost cannot be assumed to be negligible with respect to the operation cost. In this example the installation cost has been included to obtain the total ventilation cost. The installation cost is normally a discontinuous function of the flow rate. Sometimes, however, it is assumed to be proportional to the flow rate. The cost equation can in these particular cases be written:

$$X_v(Q) = c \frac{Q}{\upsilon} + abf\tau Q$$

or

$$X_v(v) = cv + abf\tau \upsilon v$$

where $v = Q/\upsilon$ is the number of air changes or the volumetric rate of the air changed;

υ is the volume of the confinement to be ventilated;

c is a constant representing the installation cost per unit rate of air changes;

a and b are constants representing the cost of electricity per unit of electrical energy, and the energy expended to condition and circulate a unit volume of air, respectively; and

f is the fraction of time in which a system operates.

Both $X_v(Q)$ and $X_v(v)$ represent the constraining functions of the cost of ventilation.

(D-5) The general objective function can then be expressed as follows:

$$U = \alpha N F_d f_t C_0 v_0 \, 0.5 \left(\frac{0.85}{v} - 0.3 \right) \tau + cv + abfv\tau\upsilon$$

Optimization can be obtained by differentiating the objective function with respect to the rate of air changes and setting it equal to zero. It is assumed that $f = f_t$. Thus:

$$-\alpha N F_d f_t C_0 v_0 \, 0.43 \frac{1}{v^2} \tau + c + abf\upsilon\tau = 0$$

but,

$$(c + abf\upsilon\tau) = \frac{X_{v_0}}{v_0}$$

where X_{v_0} is the total cost corresponding to the ventilation rate v_0.

Therefore, the optimum value of the rate of air changes, v_{op}, is found to be:

$$v_{op} = \left(\frac{v_0^2 N F_d f_t C_0 \tau \, 0.43 \, \alpha}{X_{v_0}} \right)^{1/2}$$

(D-6) If no continuous variation of v is feasible, optimization can be performed by discrete steps. The mathematical expression for the discrete steps from v_1 to v_2, and the corresponding increase of cost, (ΔX), and decrease of collective dose (ΔS_E^c) is:

$$\frac{\Delta X}{\Delta S_E^c} = \frac{X_{v_0}/\tau}{f_t N F_d C_0 v_0^2 \, 0.43} v_1 v_2$$

where the fraction X_{v_0}/τ is the annual cost incurred in achieving the rate of air changes v_0 and radon concentration C_0. Annex D_1 presents a numerical example of optimization of ventilation in the backfitting of a ventilation system of a mine, using the above formulation.

(D-7) The particular case of optimization of radiation protection in the design of a ventilation system for a mine tunnel can be exemplified assuming that (i) the ventilation cost per unit flow rate would only depend on the energy cost incurred in operating the system (this is approximately correct if only small changes in the flow rate are introduced in the optimization process), and (ii) there is no local radon source such as uranium-rich ores or radon-rich water in the gallery. Thus, the source of radon is assumed to be radium-226 distributed in rocks surrounding the mine tunnels. The emanation rate of radon is dependent on the ore grade and, as a first approximation, the average activity concentration of radon-222 in air, C, can be determined by:

$$C = \frac{JpL}{Q}$$

where J is the constant emanation rate expressed as activity released into the gallery per unit time and per unit area;

p is the perimeter of a cross section of the mine tunnel;

L is the length of the mine tunnel; and

Q is the ventilation flow rate.

(D-8) The concentration of the potential alpha energy of the daughters increases with time and, at a constant radon concentration, is approximately proportional to $t^{0.85}$, where t is the number of minutes of growth, provided it does not exceed 40 min.[33] Therefore, the potential alpha-energy concentration, ε_α, of air with a concentration, C, of radon-222 at a time t min after it was completely cleared of radon daughters can be estimated by means of the following general equation:

$$\varepsilon_\alpha = \varepsilon_{\alpha_{1'}} C \left(\frac{t}{t_{1'}}\right)^{0.85}$$

where $t_{1'}$ is 1 min; and

$\varepsilon_{\alpha_{1'}}$ is the potential alpha-energy concentration per unit concentration of radon-222 after 1 min growth (as a simplification, it may be assumed that the equilibrium of radon and its daughters will not change in the range of Q used in the optimization process).

(D-9) From the equation in para. D-8 above, the potential alpha-energy concentration at different points in the mine tunnel can be formulated. At a given work place in the mine tunnel, a small (differential) concentration of potential alpha energy ($d\varepsilon_\alpha$), which is generated by radon arising from a given location in the mine, will be proportional to the differential concentration of radon at the generating point and to the transit time from the emanating point up to the work place. The differential concentration of radon at the generating point is

$$dC = \frac{Jp \, d\chi}{Q}$$

and the transit time from the generating point up to the work place will be:

$$t = \frac{\chi\phi}{Q}$$

where ϕ is the cross-sectional area of the mine tunnel; and

χ is the distance travelled by the air from the generating point up to the work place.

Therefore, by substitution in the general formula in para. D-8,

$$d\varepsilon_\alpha = \varepsilon_{\alpha_{1'}} \frac{Jp \, d\chi}{Q} \left(\frac{\chi\phi}{t_{1'} Q}\right)^{0.85}$$

(D-10) At a work place located at a distance χ from the air inlet, the value of the total potential alpha energy concentration generated by radon emanating from the tunnel surface from the air inlet up to χ can be obtained by integrating $d\varepsilon_\alpha$. Thus,

$$\varepsilon_\alpha(\chi) = \frac{\varepsilon_{\alpha_{1'}} Jp\phi^{0.85}}{1.85 t_{1'}^{0.85} Q^{1.85}} \chi^{1.85}$$

Therefore the collective effective dose-equivalent commitment, S_E^c, incurred by a group of N individuals working in a mine tunnel at a distance χ from the ventilation air inlet and during the time t will be:

$$S_E^c = \frac{\varepsilon_{\alpha_1'} Jp\phi^{0.85}}{1.85 t_{1'}^{0.85} Q^{1.85}} \chi^{1.85} F_d N f_t \tau$$

where F_d is the dosimetric factor relating the effective dose-equivalent rate with the potential alpha energy per unit volume;

N is the number of exposed miners;

f_t is the relevant occupancy time factor; and

τ is the life time of the installation.

(D-11) Assuming, for the purpose of the example, that the ventilation cost will be limited to the operation cost, the objective function for this theoretical case can be expressed as follows:

$$U = \frac{\alpha\varepsilon_{\alpha_1'} Jp\phi^{0.85}\chi^{1.85} F_d N f_t \tau}{1.85 t_{1'}^{0.85} Q^{1.85}} + abf\tau Q$$

where a and b are constants representing the cost of electricity per unit of electrical energy, and the energy expended to condition and circulate a unit volume of air, respectively; and

f is the fraction of time in which a system operates. It is assumed that $f = f_t$.

(D-12) Optimization requires that the objective function be minimized. Therefore, differentiating the objective function with respect to the ventilation flow rate and equalizing to zero, gives the following optimum flow rate:

$$Q_{op} = \left[\frac{F_d \alpha N \varepsilon_{\alpha_1'} Jp\chi}{ab}\left(\frac{\phi\chi}{t_{1'} Q_{op}}\right)^{0.85}\right]^{1/2}$$

which can also be expressed as:

$$Q_{op} = \left(\frac{F_d \alpha N \varepsilon_{\alpha_1'} Jp\chi^{1.85}\phi^{0.85}}{abt_{1'}^{0.85}}\right)^{\frac{1}{2.85}}$$

ANNEX D_1

Numerical Examples of Optimization of Radiation Protection by the Backfitting of a Ventilation System in a Mine

(D_1-1) The example will consider whether it is worthwhile to introduce mechanical ventilation in a mine with about 400 miners, mining about 1 million tons of ore annually. The radon daughter concentration averages 1 WL before the installation of mechanical ventilation and would be about 0.1 WL after the installation. The installation costs and annual operational costs are approximately as follows:

600 m shaft	0.75	10^6 \$
300 m gallery	0.13	10^6 \$
3 fans at 90 kW	0.075	10^6 \$
Heating systems	0.05	10^6 \$
Hardware (Total)	1	10^6 \$
Electricity to 3 fans	0.05	10^6 \$ y^{-1}
Oil to heating system	0.04	10^6 \$ y^{-1}
Annual Operation Cost (Total)	0.09	10^6 \$ y^{-1}

Therefore, if the installation costs are written off over a short lifetime of a 10 year period, the total annual cost is ~0.2 10^6 \$ being equally apportioned between the installation and operation.

(D_1-2) The reduction of the collective dose is

$$\Delta S = N \Delta C F_d$$

where N is the number of miners (400 in this case);

ΔC is the differential change in the radon daughters concentration (0.9 WL in this case); and

F_d is the dosimetric factor for occupational exposure ($120\ 10^{-3}$ Sv y^{-1} WL^{-1})

Thus,

$$\Delta S = 400 \text{ man } 0.9 \text{ WL } 120\ 10^{-3} \text{ Sv y}^{-1} \text{ WL}^{-1} = 43.2 \text{ man Sv y}^{-1}$$

Therefore, the relation $\Delta X/\Delta S$ becomes:

$$\frac{\Delta X}{\Delta S} \cong 0.5\ 10^4 \ \$ \ (\text{man Sv})^{-1}$$

Accordingly, the installation and use of mechanical ventilation seems to have been worthwhile, if $\alpha > 0.5\ 10^4$ \$ (man Sv)$^{-1}$.

(D_1-3) A reduction of the radon daughter concentration in a mine by means of primarily mechanical ventilation, might involve the whole mine or only some workplaces in a gallery. In the first case it might be necessary to build a new shaft because an increased air-flow rate in the existing shaft makes the operational costs too high (the need for electricity for the fans increases as the cube of the relative increase of the flow rate). In the example given in the above paragraph, the extra annual costs would be about 0.4 10^6 \$ with no new shaft and about 0.2 10^6 \$ if a new shaft is built. Even if the radon daughter concentration is reduced to 0.01 WL, the value of $\Delta X/\Delta S$ would be set about 10^5 \$ (man Sv)$^{-1}$ and might not be worthwhile in either case.

(D_1-4) Local radiation protection problems are solved by increasing the flow rate at the work place. If this is done by changing to a tube with a cross-section proportional to the flow rate, the extra costs are proportional to the increase in the flow rate. Because of economic reasons the ventilation of the workplace by air blown from a tube is often preferred to sucking air into a tube. In the blowing case there is no build-up of radon from other sources than those at the work place. In the case of sucking air or passing air through a tunnel, there would be a build up of radon during the transportation of air through the tunnels (see Appendix D, paras. D-7 *et seq.*).

In the optimization procedure, the decreased daughter concentration and corresponding collective dose commitment can be calculated, assuming proportionality between the radon concentration and the reciprocal of the air flow rate and using an appropriate equilibrium factor F. Flow rates of 1–10 $m^3\ s^{-1}$ are not unusual in mines, corresponding to $v \cong 10\text{–}1\,000\ h^{-1}$, the exact value depending on the volume of the ventilated work place. That means that the average residence time of the air is of the order of minutes and the radon daughter activity would consist mainly of RaA. At this high ventilation rate, the factor F can be expressed approximately by the exponential function (see Appendix C, para. C-6).

$$F(v) = F_{30}\, e^{-0.019(v-30)} \quad (30\ h^{-1} < v < 100\ h^{-1})$$

The equilibrium equivalent concentration of radon (EEC) is expressed as follows (see Appendix C):

$$\text{EEC} = \frac{C_0 v_0}{v}\, 0.5\, F = \frac{C_0 v_0}{v}\, 0.5\, F_{30}\, e^{-0.019(v-30)}$$

(D_1-5) The next example considers the optimization procedure for a typical 100 m mine tunnel where five miners work continuously. The cost of increased ventilation depends, as before, on the method chosen. Increased air flow through the same tube would lead to an energy requirement proportional to the cube of the relative increase of the air flow rate. If a broader tube is used instead, the cost increases in proportion to the increase of flow rate plus the installation costs. If the latter method is used to double the ventilation rate in the example, the costs will be approximately as follows:[65]

	Installation costs		
Tube (100 m, $\phi = 70$ cm):	1 200 \$	Tube (100 m, $\phi = 100$ cm):	1 700 \$
Fan (10 kW):	2 500 \$	Fan (<20 kW):	5 000 \$
	3 700 \$		6 700 \$
	Operational costs per year		
Electricity (6 000 h):	2 000 \$		4 000 \$
	Total annual costs for 10-year lifetime		
	2 370 \$		4 670 \$

Therefore, the marginal cost becomes 2 300 \$. It has been assumed that the ventilation is in operation during 6 000 h for three shifts of workers and that the installation costs are written off over 10 years.

(D_1-6) Assuming that the number of workers is 15, that the ventilation is increased from 30 h^{-1} to 60 h^{-1} (the respective F being $F_{30} = 0.040$ and $F_{60} = 0.022$) and that $C_0 = 3.5\ 10^4$ Bq m^{-3}, the relation $\Delta X/\Delta S$ becomes 2 10^4 \$ (man Sv)$^{-1}$. A radon concentration of 3.5 10^4 Bq m^{-3} corresponds to an equilibrium equivalent concentration of 700 Bq m^{-3} or 0.2 WL. Accordingly, if the radon daughter concentration is more than 0.2 WL, with a volumetric rate of air changed of 30 h^{-1}, it would be worthwhile at least to double the ventilation rate under the assumption that $\alpha > 2\ 10^4$ \$ (man Sv)$^{-1}$.

APPENDIX E

Algebraic Example of Optimization of Radiation Protection by the Design of a Simple Air-Cleaning System

(E-1) The differential equation representing a typical air-cleaning process is:

$$\frac{\mathrm{d}C(t)}{\mathrm{d}t} = \frac{\dot{A}}{V} - C(t)\left[\frac{Q}{\upsilon}\left(1 - \prod_{1}^{\theta} p\right)\right]$$

where p is the penetration of one decontamination unit, $p = 1 - \xi$, where ξ is the efficiency of one decontamination section of the system which might be assumed to be constant, under the assumption that either a prefilter is included or the air is sufficiently clean of saturating particles; $\xi = 0.9997$ if individual units of high efficiency particulate (HEPA) filters are used;

θ is the number of decontamination units in series; and

all other variables are as described in Appendix B.

Then, assuming again (see Appendix B) that $Q \gg \lambda\upsilon$ and $C(\mathrm{o}) = 0$, in equilibrium C can be expressed as follows:

$$C = \frac{\dot{A}}{Q\left(1 - \prod_{1}^{\theta} p\right)}$$

(E-2) The operative cost of air cleaning systems will include two components: one related to the circulation of air and the other to the decontamination. The first can be determined similarly to the ventilation cost; the latter is basically proportional to θ. Thus, if the cost of the installation, X_I, is assumed to be independent of θ and Q (which can be realistic if small changes in θ and Q occur as a result of the optimization process), the total cost will be:

$$X = (abQ + \delta\zeta\theta)\tau + X_I$$

where δ is a constant representing the cost per decontamination unit; and

ζ is the replacement frequency.

The equation above assumes that no change in the number of decontamination units would be needed as a consequence of the variations in the flow rate resulting from the optimization process. If the variations in the flow rate are large enough, the above assumption may not be valid. In this case, the value of δ needs to be multiplied by a factor proportional to the flow rate divided by the nominal flow of each decontamination unit. Furthermore, it was assumed that only one branch of decontamination units in series is included, otherwise, the second term in the parenthesis should be multiplied by the number of parallel branches.

(E-3) The collective effective dose equivalent commitment incurred by people working in a confined space being decontaminated by the air-cleaning system can be formalized as follows:

$$S_{\mathrm{E}}^{\mathrm{c}} = f_t N \tau F_d \frac{\dot{A}}{Q\left(1 - \prod_{1}^{\theta} p\right)}$$

where the dosimetric factor, F_d, has been assumed to be an average value corresponding to the mean age of the people residing in the place. The constraining function of the cost detriment will be the following:

$$Y = \alpha f_t N \tau F_d \frac{\dot{A}}{Q\left(1 - \prod_1^{\theta} p\right)}$$

(E-4) Therefore, when optimizing air-cleaning systems, the objective function can be formulated as follows:

$$U = \alpha f_t \tau N F_d \frac{\dot{A}}{Q\left(1 - \prod_1^{\theta} p\right)} + (abQ + \delta\zeta\theta)\tau + X_I$$

(E-5) Minimizing the objective function results in a set of optimum flow rates, one for each number of decontamination units, such as:

$$Q_o = \left(\frac{\alpha}{ab\left(1 - \prod_1^{\theta} p\right)} f_t N F_d \dot{A} \right)^{1/2}$$

Since the number of decontamination units, θ, is usually limited, it will be simple to assess a set of Q_o (one for each decontamination section) and to determine the value of the objective functions for each one of them. The value of Q_o giving the minimum of all these values of objective functions would be the optimum flow rate, and the corresponding θ_o would be the optimum number of decontamination units.

APPENDIX F

Example of a Procedure for Optimization of Radiation Protection through the Control of Releases of Radioactive Materials

(F-1) A simple procedure to obtain the optimum solution from a set of alternatives for controlling releases is to tabulate both the cost of, and the collective dose from, each alternative, as shown in the table below; the incremental changes of these variables between alternatives and their ratio can be easily assessed.

Alternatives	A	A→B	B	B→C	C	C→D	$n-1 \to n$	n
Cost of Protection (X)	X_A		X_B		X_C			X_n
Collective Dose (S)	S_A		S_B		S_C			S_n
ΔX		$X_B - X_A$		$X_C - X_B$		$X_D - X_C$	$X_n - X_{n-1}$	
$-\Delta S$		$S_A - S_B$		$S_B - S_C$		$S_C - S_D$	$S_{n-1} - S_n$	
$-\frac{\Delta X}{\Delta S}$		$\frac{X_B - X_A}{S_A - S_B}$		$\frac{X_C - X_B}{S_B - S_C}$		$\frac{X_D - X_C}{S_C - S_D}$	$\frac{X_n - X_{n-1}}{S_{n-1} - S_n}$	

(F-2) Alternative A might mean no control at all, ($X_A = 0$), or a minimum control needed to maintain individual doses below some preset level. The optimum result is obtained for the value of the last line, being higher than the selected value of α and closer to it. Annexes F_1 and F_2 present numerical examples using this procedure.

ANNEX F_1

Numerical Example of Optimization of Radiation Protection through the Control of Gaseous Releases from a Boiling Water Reactor

(F_1-1) The release of short-lived gases from a Boiling Water Reactor is discussed as an example of the application of optimization of an effluent control system based on decay in delay. In BWRs, continuous removal of non-condensible gases in the steam flow occurs via the main condenser air ejector system. The gases enter the gaseous waste stream primarily at this point. Secondary sources include off-gassing of process fluids.

(F_1-2) The example applies to a specific model of BWR, and the cost of the alternatives identified refers to the situation in a particular country.[5] The assessment of collective effective dose-equivalent commitment is based upon the assumption of 0.1% of fuel with pinhole damage, information on the operational characteristics, the effectiveness of each effluent treatment alternative and environmental dosimetric models.[65,69]

(F_1-3) The alternative levels of control based on decay considered are:

(A) Sandtank, as a delay allowing for decay (of the type used in the reactors Oskarshamn 1 and 2).

(B) Sandtank plus recombiner (of the type used in reactors Barsebäck 1 and 2).

(C) Sandtank plus recombiner plus activated charcoal column (of the type used in reactors Forsmarkt 1 and 2).

(D) Type C plus an inactive gland seal system.

(F_1-4) In order to ensure compliance with the limit equation (individual doses should not exceed the fraction of the dose limit used as "source upper bound"), option A is considered as a minimum requirement. The dose in the critical group, which would exceed the annual upper bound of a few hundred microsievert with no control at all, becomes $2\ 10^{-4}$ Sv y^{-1} (20 mrem in a year) with option A.

(F_1-5) The collective effective dose-equivalent commitment remaining after each alternative (for an assumed plant life of 40 years), and the costs of each alternative (including installation cost) are shown in the table below, together with the application of the optimization technique:

Alternatives	A	A→B	B	B→C	C	C→D	D
S_E (man Sv)	120		1.60		0.12		0.08
X (10^6 \$)	2.32		3.26		4.66		9.32
ΔX (10^6 \$)		0.94		1.4		4.66	
ΔS (man Sv)		118.40		1.48		4	
$\frac{\Delta X}{\Delta S}$ \$ (man Sv)$^{-1}$		7 900		$9.46\ 10^5$		$116.5\ 10^6$	

(F_1-6) Using a range of values 10^4–2 10^4 \$ (man Sv)$^{-1}$ for α, the table indicates the selection of alternative B as the result of optimization. Individual annual doses in the critical group are about 10^{-6} Sv for alternative B.

ANNEX F_2

Numerical Example of Optimization of Radiation Protection through the control of Iodine-129 from a Reprocessing Plant

(F_2-1) The release of iodine-129 from reprocessing plants is discussed as an example of optimization of release control based on effluent decontamination. The example refers to a postulated reprocessing plant handling 60 GW(e)y of spent fuel per year.[52]

(F_2-2) The radioactive half-life of iodine-129 is 1.7 10^7 years. Effluent treatment systems can remove much of the iodine from the effluent, and provisions can be made to isolate the collected iodine from the environment. In view of the extremely long half life of iodine-129 and little direct experience of its management there is considerable uncertainty in the performance of isolation techniques such as: conversion to stable chemical compounds; encapsulation in relatively inert materials, and entombment at great depth in the earth or under seabeds. In lieu of definitive information to the contrary, the assumption can be made for this example that the isolation will be achieved for only a small fraction of the radioactive half-life, say 10^4 years. It can also be assumed that iodine-129 released from isolation will be dispersed in the same manner as it would have been, if released from the plant section. The relevant part of the collective dose commitment in this example is the incomplete collective dose commitment integrated over 10^4 years; i.e. the difference between the collective dose commitment by immediate release and by delayed release:

$$S_E^\tau = \int_0^\infty \dot{S}(t)\,dt - \int_\tau^\infty \dot{S}(t)\,dt = \int_0^\tau \dot{S}(t)\,dt$$

where τ is 10^4 year.

(F_2-3) The alternative options for control are:

Option	*Decontamination Factor*
(A) None	1
(B) Silver zeolite retention on the dissolver off-gas	100
(C) Silver zeolite retention on the total off-gas	500

In this example, the annual doses to the critical group are quite small for any option and no minimum option is required.

(F_2-4) Calculating both cost and collective dose commitment for 20 years of operation, and taking 10^4 years for truncation of the collective dose commitment assessed using the UNSCEAR dosimetric models,[69] the following results are obtained:

Alternatives	A	A→B	B	B→C	C
$S_E^{10^4 y}$ (man Sv)	2.52 10^3		2.52 10^1		5.04
X (10^6 \$)	0		2.4		4.8
ΔX (10^6 \$)		2.4		2.4	
ΔS (man Sv)		2.49 10^3		2.02 10^1	
$\frac{\Delta X}{\Delta S}$ \$ (man Sv)$^{-1}$		9.6 10^2		1.02 10^5	

(F_2-5) Again, using a range of 10^4–2 10^4 \$ (man Sv)$^{-1}$ for α, the table indicates the selection of alternative B as the result of optimization. As indicated before, individual doses in the critical group are very small and do not have a limiting effect.

APPENDIX G

Example of Optimization of Radiation Protection in Nuclear Medicine Operations

(G-1) An example of optimization of radiation protection in nuclear medicine operations will be discussed. The steps to be applied in order to optimize radiation protection in nuclear medicine operations are the following:

(a) Identification of the various combinations of radionuclide and measuring apparatus which are available to carry out a given type of diagnostic examination with comparable diagnostic effectiveness. For example, for the case of thyroid scanning, nuclides like iodine-131, iodine-123 or technetium-99m can be used. Similarly, various types of mechanical scanners, with various levels of sensitivity and accuracy, as well as gamma cameras, can be used.

(b) For each of the above combinations of radionuclide-measuring apparatus, the radionuclide dosage required for a satisfactory diagnostic result should be assessed. For example, for thyroid scanning, typical administered activities are in the order of 10^6 Bq for iodine-123 and of 10^8 Bq for technetium-99m. These values can vary within a reasonably wide range according to the type of measuring apparatus adopted.

(c) For each of the above combinations the average individual effective dose equivalent to patients and workers for each diagnostic examination should be assessed. It should be noted that, although in this example occupational and patient components of the exposure are summed, they could, in general, be treated separately. This assessment is easy for the effective dose equivalent averaged over the patients, $\bar{H}_p$ ($\bar{H}_p = \sum_i d_i f_d$), where d_i is the administered activity of radionuclide i and f_d is an appropriate dosimetric factor describing the effective dose equivalent per unit administered activity.

(G-2) The average effective dose equivalent to individual workers is the sum of two components: (i) $\bar{H}_e$, the average dose due to the carrying out of a single radioisotope administration and diagnostic examination; and, (ii) $\bar{H}_{\text{env}}$, the average dose due to the radiation levels in the working environment and to the manipulation during storage, dilution and other operations. The first component is proportional to the administered activity per patient. The second component takes into account the influence on the workers' exposure of the different frequencies and types of operations connected with the delivery, arrival, storage, dilution and radiochemistry of the basic radioisotope solutions.

(G-3) For each of the above combinations, assuming that N_w (the number of workers) and N_p (the number of patients) are kept constant, the collective effective dose equivalent (or the appropriate collective organ dose equivalent) to the workers and the patients can be calculated as:

$$S = N_w\left[\bar{H}_e \frac{N_p}{N_w} + \bar{H}_{\text{env}}\right] + N_p \bar{H}_p$$

where N_p/N_w is the average number of patients serviced per worker.

For each combination the cost involved should also be assessed. The total cost X can be calculated as the sum of X_a (cost of the measuring apparatus), X_o (operational cost including manpower) and X_r (cost of radioisotope supply). As a first approximation, X_o can be assumed as constant.

(G-4) If a specific value of α has been established, the values of the objective function can be calculated. Then, the various combinations can be ranked according to decreasing values of $(X + \alpha S)$ and the option for which this sum is the lowest can be selected as the optimized one. Alternatively, the various combinations considered can be ranked according to increasing values of X (and, possibly, of decreasing values of S). Then, the simple formula given in para. 107 for optimization in the case of discrete variables can be applied to each pair of consecutive combinations, and an iterative process should be carried out, as mentioned in para. 108, testing increasingly high levels of radiation protection and stopping for that combination for which the value of the expression:

$$-\frac{{}_{\mathrm{B}}X - {}_{\mathrm{A}}X}{{}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E}$$

is the highest below α.

(G-5) In this simple example concerning radioisotope diagnostic procedures the assumption was made that the benefit of the practice, expressed by the quality of diagnostic information, was kept constant with the variation of radionuclide and measuring apparatus, and, therefore, with the variation of radiation protection level achieved. This might not be the case in other types of diagnostic examinations, particularly using x rays the quality of which is affected by the exposure level (see paras. 179 *et seq.*). Furthermore, the example assumed that the collective dose commitment, due to the production of the relevant amount of the nucleides involved, does not change with the alternative options.

APPENDIX H

Example of Optimization of Radiation Protection in the Domestic Use of Natural Gas

(H-1) An example is presented of the optimization of radiation protection in a situation where natural gas is used domestically. The source term to be defined includes the production rate Q of natural gas containing radioactive material, and its activity content in terms of average concentration at the point of utilization $\bar{C}$. $\dot{A} = Q\bar{C}$ will, therefore, be the source term, i.e. the total activity available yearly for exposure of a population through different pathways in the domestic use of gas. If R_h is the average per caput gas consumption rate for heating purposes, R_c the average per caput consumption rate for cooking purposes, and R_{nh} the corresponding value for other domestic uses (e.g. water-heaters, refrigerators and clothes-driers), then the number of individuals exposed, N, will be:

$$N = \frac{Q}{R_h + R_c + R_{nh}}$$

(H-2) Studies on this problem applied to tritium present in natural gas stimulated by underground nuclear explosions, or to radon and its daughters present in natural gas, have demonstrated that exposure in homes to gas combustion products from unvented appliances or heaters is the critical exposure pathway, considering only direct exposure.[3] Another critical pathway could be the ingestion of food cooked with this gas; this is particularly relevant to the case of gas from stimulated wells. Therefore, the average individual effective dose equivalent, $\bar{H}_E$, will be the sum of two contributions respectively due to inhalation (H_{E_i}) and to ingestion (H_{E_f}) of food cooked with the contaminated gas:

$$\bar{H}_E = H_{E_i} + H_{E_f} = \bar{C}(R_h + R_c + R_{nh})F_{d_i} + \bar{C}R_c F_{d_f}$$

where F_{d_i} and F_{d_f} are respectively the dosimetric factors for inhalation and ingestion, expressed in Sv per Bq in the source gas, and the corresponding collective dose commitment will be:

$$S^c_E = N(H_{E_i} + H_{E_f}) = N\bar{C}[(R_h + R_c + R_{nh})F_{d_i} + R_c F_{d_f}]$$

$$S^c_E = \frac{Q\bar{C}}{R_h + R_c + R_{nh}}[(R_h + R_c + R_{nh})F_{d_i} + R_c F_{d_f})]$$

$$S^c_E = Q\bar{C}\left(F_{d_i} + \frac{R_c}{R_h + R_c + R_{nh}} F_{d_f}\right)$$

(H-3) On the other hand, the cost of the installation for the treatment and purification of gas can be expressed by:

$$X = X_I + X_o$$

where X_I is the cost of installation; and

X_o is the cost of operation, including maintenance, energy and manpower.

(H-4) As stated in the technical section, many optimization processes are in discrete steps, both X and S being discrete instead of continuous variables. In this case, considering options A and B for treatment and purification of gas such that ${}_{\mathrm{B}}X > {}_{\mathrm{A}}X$ and ${}_{\mathrm{B}}S^c_E < {}_{\mathrm{A}}S^c_E$ as shown in para. 107, the condition of optimization is satisfied when:

$$-\frac{{}_{\mathrm{B}}X - {}_{\mathrm{A}}X}{{}_{\mathrm{B}}S^c_E - {}_{\mathrm{A}}S^c_E} \leq \alpha$$

If all other conditions of utilization remain unchanged, the controlling parameters in the optimization process are the costs of the gas treatment and purification system and the corresponding average concentration of the considered radionuclide in the gas at the points of utilization. These are:

$${}_{\mathrm{A}}X = X_{I_{\mathrm{A}}} + X_{o_{\mathrm{A}}}$$

$${}_{\mathrm{B}}X = X_{I_{\mathrm{B}}} + X_{o_{\mathrm{B}}}$$

$${}_{\mathrm{A}}S^c_E = Q\bar{C}_{\mathrm{A}}\left(F_{d_i} + \frac{R_c}{R_h + R_c + R_{nh}} F_{d_f}\right)$$

$${}_{\mathrm{B}}S^c_E = Q\bar{C}_{\mathrm{B}}\left(F_{d_i} + \frac{R_c}{R_h + R_c + R_{nh}} F_{d_f}\right)$$

$\bar{C}_{\mathrm{A}}$ and $\bar{C}_{\mathrm{B}}$ being the average concentrations of the considered radionuclide in the gas, under the treatment and purification conditions A and B, respectively.

(H-5) The condition of optimization will, therefore, be satisfied by the following equation:

$$\frac{(X_{I_{\mathrm{B}}} - X_{I_{\mathrm{A}}}) + (X_{o_{\mathrm{B}}} - X_{o_{\mathrm{A}}})}{(\bar{C}_{\mathrm{A}} - \bar{C}_{\mathrm{B}})Q\left(F_{d_i} + \frac{R_c}{R_h + R_c + R_{nh}} F_{d_f}\right)} \leq \alpha$$

$$\frac{(X_{I_B}-X_{I_A})+(X_{o_B}-X_{o_A})}{\bar{C}_A-\bar{C}_B} \leq Q\alpha\left(F_{d_i}+\frac{R_c}{R_h+R_c+R_{nh}}F_{d_f}\right)$$

If more than two options are available, optimization must be achieved by any of the processes presented in para. 108.

LIST OF SYMBOLS

a	Cost of electricity per unit of electrical energy.
$a_{n\gamma}$	Annuity factor; i.e. sum of discount factors at the discount rate, γ, over n years time.
$\dot{A}$	Radioactive material input or output rate.
$\dot{A}_{ik}$	Radioactive material leakage rate of radionuclide i from a containment k.
$\mathring{A}_i$	Activity of radionuclide i potentially released annually.
b	Electrical energy necessary in order to circulate and condition a unit volume of air.
B	Net benefit from the introduction of a practice.
$B(\mu w)$	Dose build-up factor of a shielding of thickness w and built with a material having a dose attenuation coefficient μ.
c	Cost of installation of ventilation per unit rate of air-changes.
$C \equiv C(\infty)$	Concentration of radioactive material in air at equilibrium.
$C(0)$	Initial concentration of radioactive material in air.
$C(t)$	Concentration of radioactive material in air at time t.
$\bar{C}$	Average concentration of radioactive material.
C_{E_i}	Concentration of nuclide i in the process effluent stream.
$C_i(Q)$	Equilibrium concentration of radioactivity of radionuclide i under a ventilation flow rate Q.
C_{I_i}	Concentration of nuclide i in the incoming process stream.
$C_{n\gamma}$	Capital recovery factor for discount rate γ and for a number of periods, n, corresponding to the lifetime of the project.
d	Derivative operator.
d_i	Dosage of radionuclide i.
D	Decontamination factor.
D_i	Decontamination factor for radionuclide i.
EEC	Equilibrium equivalent concentration of radon.
f	Fraction of time in which a system operates.
f_d	Dosimetric factor converting activity in dose.
f_t	Relevant occupancy time factor.
f_{t_j}	Occupational time factor of a group j of exposed people; it denotes the fraction of time during which individuals in group j are exposed to radiation from a source or to contamination from an environment.
$f(H)$	Function of individual doses, which depends on risk aversion attitudes and national or managerial regulations.
F	Equilibrium factor, ratio of the total potential alpha energy for a given daughter concentration to the total potential alpha energy of the daughter concentration if they are in equilibrium with radon.
$F(S)$	Function giving a quantitative relationship between the collective dose, S, and the maximum annual effective dose-equivalent commitment, H^*.

F_d — Dosimetric factor converting activity concentration in dose rate (i.e. the effective dose-equivalent rate incurred by exposed individuals, per unit concentration of radioactive material in air), which is assumed to be an average value corresponding to the mean age of the exposed people.

F_{d_f} — Dosimetric factor, f_d, for ingestion.

F_{d_i} — Dosimetric factor, f_d, for inhalation.

$F_\imath$ — Expected frequency of a deleterious effect $\imath$.

$g_\imath$ — Factor measuring the severity of a deleterious effect $\imath$.

g_T — Factor measuring the severity of a deleterious effect for tissue T.

G — Detriment.

G_H — Objective health detriment.

$G_{H,1}$ — Objective health detriment to one person.

h — Height (of a wall shielding).

H_E — Sum of the weighted organ dose equivalent or effective dose equivalent.

H_{E_i} — Effective dose equivalent due to inhalation.

H_{E_f} — Effective dose equivalent due to ingestion.

H_{gon} — Dose equivalent in gonads.

H_L — Relevant dose-equivalent limit or fraction of it assigned by the competent authority as upper bound for a practice.

H_{skin} — Dose equivalent in skin.

H_{thy} — Dose equivalent in thyroid.

H_T — Average dose equivalent received in tissue T.

$H_z(\omega)$ — Individual effective dose equivalent at a radiation protection level ω.

H^* — Maximum annual effective dose-equivalent commitment.

$\dot{H}$ — Dose-equivalent rate.

$\dot{H}_E$ — Effective dose-equivalent rate.

$\dot{H}_L$ — Derived limit of effective dose-equivalent rate, compliance of which implies virtual certainty of compliance with the relevant dose limits or with fractions of them assigned by the competent authority as upper bounds for practices.

$\dot{H}_u$ — Maximum effective dose-equivalent rate, which would be incurred by a hypothetical receptor located in contact with the external face of an initial minimum thickness shield ($\dot{H}_u \leq \dot{H}_L$).

$\bar{H}_E$ — Average effective dose equivalent.

$\bar{\dot{H}}_E$ — Average effective dose-equivalent rate.

$\bar{H}_e$ — Average dose due to the carrying out of a single radioisotope administration and diagnostic examination.

$\bar{H}_{\mathrm{env}}$ — Average effective dose equivalent due to the radiation level in the working environment.

$\bar{H}_p$ — Average dose to a patient.

i — Given radionuclide.

j — Given group of exposed people.

J — Emanation rate of radon per unit area of a gallery.

k — Given containment of radioactive material.

l — Length of wall-shielding.

ℓ — Given subsystem of radiation protection.

L — Length of mine tunnel.

n — n^{th} event; e.g. the n^{th} year.

N — Number of individuals.

N_j	Number of individuals in a group j.
N_p	Number of patients.
N_w	Number of workers.
$N(H_E)$	Population spectrum in effective dose equivalent from the source.
$N(H_E)\,dH_E$	Number of individuals receiving from the source an effective dose equivalent in the range H_E to $H_E + dH_E$.
p	Perimeter of a cross section of mine tunnel.
p_ι	Probability of occurrence of a deleterious effect ι.
p_T	Probability of suffering a stochastic effect in tissue T.
P	Basic production cost of a practice excluding the cost of radiological protection.
Q	Flow rate (e.g. ventilation flow rate, gas flow rate).
Q_o	Optimized ventilation flow rate.
Q_L	Minimum limiting ventilation flow rate, the use of which implies virtual certainty of compliance with the dose limit.
r_Q	Fractional increase of flow rate.
r_T	Risk factor per unit dose equivalent in tissue T.
R	Total individual risk of incurring a deleterious effect as a result of whole-body irradiation (per unit dose equivalent).
R_h	Average per caput gas consumption rate for heating purposes.
R_c	Average per caput gas consumption rate for cooking purposes.
R_{nh}	Average per caput gas consumption rate for domestic uses other than heating and cooking.
s_i	Collective effective dose-equivalent commitment per unit activity of nuclide i.
S_E	Collective effective dose equivalent.
$\dot{S}_E$	Collective effective dose-equivalent rate.
S_E^c	Collective effective dose-equivalent commitment.
S_E^τ	Incomplete collective effective dose-equivalent commitment over time τ.
S_o	Collective dose resulting from the optimized level of radiation protection.
t	Time.
$t_{1'}$	One minute time.
T	Given tissue.
U	Objective function.
V	Gross benefit from the introduction of a practice.
w	Shielding thickness.
w_o	Optimized shielding thickness.
w_T	Factor representing the fraction of risk resulting from tissue T when the whole body is irradiated uniformly.
W	Potential alpha energy content per unit activity of radon in equilibrium with its short-lived daughters.
WL	Working level defined as any combination of short-lived radon daughters per litre of air that will result in the emission of 1.3 10^5 MeV of alpha energy in their decay to lead-210.
WLH	Working level hour.
WLM	Working level month.
WLY	Working level year.
X	Cost of radiation protection.
X_a	Annual cost of radiation protection.
X_c	Initial capital cost of radiation protection.

X_F	Future amount that a present value, X_p, will accumulate at a given interest rate.
X_I	Installation cost of radiation protection.
X_o	Operational cost of radiation protection.
X_P	Present value of the cost of radiation protection.
X_S	The cost of shielding installed.
X_υ	Cost of ventilation.
X_V	Cost of shielding installed per unit volume of shielding material.
$\dot{X}_o$	Rate of operating cost of radiation protection.
Y	Cost of detriment.
Y_H	Cost of the objective health detriment.
Y_1; Y_2;	... Cost of other components of the detriment.
α	Dimensional constant expressing the monetary cost assigned to a unit of collective dose for radiation protection purposes.
β	Dimensional constant expressing the monetary cost assigned to a unit of a component of the detriment other than the objective health detriment.
γ	Discount rate.
γ_n	Discount factor to be applied in the n^{th} year at a discount rate γ.
Γ	Effective attenuation coefficient, including the effects of build-up.
∂	Partial derivative operator.
δ	Constant representing the cost per decontamination unit.
Δ	Finite increment.
ε_α	Potential alpha energy concentration.
$\varepsilon_{\alpha 1'}$	Dimensional constant representing the potential alpha energy concentration per unit concentration of radon after 1 min growth.
ζ	Frequency of replacement of a decontamination unit.
θ	Number of decontamination units in series.
ι	Given deleterious effect of radiation.
κ	Correction factor to take account of the various uncertainties related to the assessment of the equilibrium factor.
λ	Decay constant.
λ_i	Radioactive decay constant of nuclide i.
μ	Dose attenuation coefficient.
υ	Volume of an environment or containment.
υ_D	Volume available for decay.
ξ	Efficiency of a decontamination unit.
Ξ	Dimensional constant defining radon activity concentration per unit working level.
$\prod_n$	Process of finding the product of n quantities.
ρ	Quotient between the average effective dose-equivalent rate to which individuals in a group of people are exposed and the maximum effective dose-equivalent rate on the shielding surface.
τ	Lifetime of a radiation protection system or isolation time with radiation protection purposes.
$\tau_{A,B}$	Isolation time of system A,B.
ϕ	Cross-sectional area of a mine tunnel.
χ	Distance travelled by the air in a ventilated gallery.
ψ	Constraining function.

ω	Parameter representing a level of radiation protection.
ω_o	Optimized value of ω.
$\Sigma_n, \sum_n$	Process of finding the addition of n quantities.
\$	Unit of an ideal, non-inflationary, currency.
US\$	Dollars of the United States of America.

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