JUSTIFICATION AND OPTIMIZATION IN RADIATION PROTECTION

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1. INTRODUCTION

1. To meet the objectives of radiation protection the ICRP (1) has recommended the use of a system of dose limitation composed of the following requirements: 1) Justification of practices involving radiation exposures; 2) Optimization of the level of protection for such practices; 3) Individual dose limitation. The third requirement is individual-related, and is the continuation of previous recommendations limiting the risk to individuals from exposure to radiation. The first two requirements, on the other hand, are source-related. They apply even if all individuals are so well protected that their risk is negligible, requiring that the radiation detriment from a given source be reduced by increasing protection to the optimum level, and that the practice (with its remaining radiation detriment) be justified by benefits.

2. The ICRP has recommended the use of cost-benefit analysis in the assessment of justification of practices involving radiation exposures and in the optimization of radiation protection (1). The concept of "net benefit" from the introduction of a practice involving radiation exposures was defined in that publication in symbolic form as:

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

where B is net benefit from the introduction of the practice, V is the gross benefit, P is all production costs excluding protection costs, X is the cost of achieving a selected level of protection and Y is the cost of detriment associated with that level of protection.

2. QUANTIFICATION OF THE RADIATION DETRIMENT

3. The application of cost-benefit analysis requires the assignment of quantitative values to X and Y in all cases, and for some applications to V and P. While P and X costs are readily expressed in monetary terms, V may contain components difficult to quantify. The quantification of Y, the cost of the radiation detriment, is regarded as the most problematic and the most controversial of the quantifications. Nevertheless, it is essential for the application of cost-benefit analysis to radiation protection.

4. Optimization of protection takes place in a region of low individual doses, always smaller than a fraction of the dose limits. Therefore, only the induction of somatic and genetic stochastic effects of radiation will contribute to the deleterious health consequences, as non-stochastic effects would be totally prevented. In order to deal with the risk of stochastic effects, the ICRP uses the quantity:

$$H_E = \sum_T w_T H_T$$

where H_E is a sum of weighted organ dose equivalents, called the "effective dose equivalent", w_T is a factor representing the fraction of risk resulting from tissue T when the whole body is irradiated uniformly, and H_T is the dose equivalent in tissue T. The recommended values of w_T are given in ICRP publication 26; and additional value for skin exposures has also been provided by the ICRP (2).

5. The "detriment" in an irradiated population group is defined as the expectation of the harm incurred, taking into account not only the probabilities of each type of deleterious effect but also the severity of the effects. If P_i is the risk of suffering the effect i, the severity of which is measured by a factor g_i, then the detriment G in a group of N persons is $G = N \sum_i P_i g_i$.

6. For stochastic effects it is assumed that increments of risk are proportional to increments of dose. Then p_T, the probability of suffering a stochastic effect in tissue T can be taken to be proportional to the average dose received in that tissue

$$p_T = r_T H_T$$

r_T being a risk factor per unit dose equivalent. When this is substituted into the equation for detriment, the detriment of one person is given by

$$G_1 = \sum_T r_T H_T g_T$$

Several approaches are possible to quantify the severity factors g_T (3). For radiation protection purposes it could be assumed as a first approximation that the detriment is dominated by the induction of fatal malignancies and of servere genetic effects in the first two generations, assigning a severity factor of one to all these effects. In this case, the effective dose equivalent would be proportional to the individual health detriment because

$$G_1 = \sum_T r_T H_T = R H_E,$$

where R is the total risk for whole body irradiation, and $w_T = \frac{r_T}{R}$. The value of R is taken to be 1.65×10^{-2} Sv^{-1} (3).

7. This first approximation, however, neglects the contribution to the detriment of subsequent generations after the second, and of non-fatal malignancies, which are not taken into account in the definition of effective dose equivalent. The contribution of subsequent generations to the detriment could be roughly taken into account by adding a term $w_{gon} H_{gon}$ to the effective dose equivalent. Non-fatal malignancies could probably be neglected when compared to fatal malignancies. Several attempts to quantify their contribution, which are very controversial, support the idea of neglecting such contribution to the detriment.

8. The detriment is an extensive quantity. The detriment from a given source is therefore the summation of the detriments of all individuals irradiated by the source, either at present or in

the future. It follows (4) that the detriment from the source k, G_k, is given by

$$G_k = R \sum_i N_i \bar{H}_{E,i} = R.S^c_{E,k}$$

where R is the risk factor for whole body irradiation, N_i is the number of individuals receiving an average effective dose equivalent $\bar{H}_{E,i}$ from the source, and $S^c_{E,k}$ is the collective effective dose equivalent commitment from the source.

9. As the detriment is an expectation of death (and of serious genetic harm), the assignment of a cost to the detriment involves some valuation of human life. In fact, countless policy decisions affect the incidence of death and none tries to minimize this incidence regardless of cost. Implicit in any of such decisions, therefore, is some valuation of human life.

10. A key feature of the modern approach for taking account of life in cost-benefit analysis is that it does not value life as such, but only changes in the probability of death. Being the detriment a mathematical expectation of death, the assignment of a cost to the detriment would fit well with the quoted approach. As the detriment is proportional to the collective effective dose equivalent commitment, the problem reduces to the assignment of a monetary value to the unit of collective effective dose equivalent. Obviously, this assignment is a value judgement rather than a scientific determination. It has been attempted by assigning values to the increased probability of death, or by observation of the values society actually is willing to pay to reduce exposures in given practices.

11. With the first approach, values ranging from 20 to 200 dollars per man rem can be deduced from assessments of "cost of a statistical life" and a risk of 1 to 2 10^{-4} per rem. The second approach gives somewhat higher values for a man rem, up to a few hundred dollars. A value of about 100 to 200 dollars per man rem seems to be adequately representative, and could be used for planning purposes in those cases where the competent authority has not yet established the value to be used.

12. For the purpose of cost-benefit analysis in radiation protection, therefore, the cost of the detriment can be expressed as:

$$Y = \alpha\, S^c_E$$

where Y is the cost of detriment, α is the monetary cost assigned to the unit of collective effective dose equivalent and S^c_E is the collective effective dose equivalent commitment associated with the level of protection under consideration.

13. Problems associated with costs and detriments occurring over different time periods are frequent, especially when a practice leads to environmental contamination by long lived radionuclides and therefore to subsequent exposure in future populations. The concept of collective effective dose equivalent commitment allows the calculation of detriment in these cases giving the same weight to present and future detriments, which is not the usual practice in

other types of human judgements, which involve the traditional economical technique of discounting.

14. However, on ethical grounds it has been argued that discounting perhaps be properly applied within the time period of one generation, but that it should not be applied when a substantial part of the detriment will occur in future generations. Some have also expressed the opinion that it is not valid to discount the cost of the detriment (even if manifested in the future) committed from one year of practice, because only the present decision was relevant and the future harm was unavoidable. However, it would be legitimate to discount the cost of the detriment committed successively year after year of the practice.

3. OPTIMIZATION

15. A basic requirement of radiation protection is that all doses should be kept "as low as it is reasonably achievable", taking into account social and economical considerations. This requirement is usually called "optimization" of radiation protection and consists in reducing the collective dose (and thus the detriment) to a value such that further reductions are less significant than the additional efforts required to achieve such reductions.

16. Optimization, therefore, consists in an interplay of the cost of protection and the cost of the remaining detriment, in such a way that

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

where X is the cost of protection, and Y is the cost of the radiation detriment, both at a level of protection represented by w (e.g., shielding thickness, ventilation rate, alternative options of protective equipment, etc.). It should be noted that w, and X(w) and Y(w), can in some cases be continuous, while in other cases they take only discrete values. 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, as defined in paragraph 2.

17. Some of the technical difficulties of optimization are related to the boundary condition introduced by the dose limits. As the limits apply to the combined exposure from all sources (except those specifically excluded), it is necessary to use a fraction of the limit as a boundary condition for the optimization of a given source. It is not the purpose of this paper to review the criteria to set such source upper bound, L, but to show its use as a boundary condition.

18. In the ideal optimization case, there is only one exposed group of individuals and one protection parameter or a simple set of protection options. Additionally, a basic requirement of this ideal case is the existence of a quantitative relationship between the collective effective dose equivalent commitment S, and the maximum annual effective dose equivalent, H*, such as H* = f (S). Taking the detriment to be proportional to the collective dose (paragraph 12) and using the symbols defined previously, optimization in the ideal case can be expressed as the set of conditions (4)

$$(1) \quad X(w) + \alpha\, S(w) = \text{minimum}$$
$$(2) \quad f(S) \leq L.$$

19. The minimum for the first expression, usually called the objective function, can be obtained by differentiation and making the result equal to zero:

$$\frac{dX}{dw} = -\alpha \frac{dS}{dw}, \text{ or as usually presented,}$$

$$\left(\frac{dX}{dS}\right)_{S_o} = -\alpha$$

The optimized value S_o correspond to a given optimum protection parameter w_o and a given protection cost, S_o, because X can be expressed as a function of S, the function being called the constraining function.

20. The optimized value S_o must, however, comply also with the second condition of paragraph 18, namely the limit equation $f(S_o) \leq L$. Therefore, optimization is achieved at a value of collective effective dose equivalent commitment, S_o, such that

$$\left(\frac{dX}{dS}\right)_{S_o} = -\alpha$$

provided that $f(S_o) \leq L$, and at a value $S_o = f^{-1}(L)$ in all other cases.

21. Examples of application of this procedure of optimization have been published for radiation shielding and for ventilation design in installations handling radioactive materials, in uranium mines and in buildings (in relation to radon) (4)(5) (6). In many other practical cases of optimization assessments, the changes in protection levels are achieved in finite increments, both X and S being discrete instead of continuous variables. The decision of going from a level of control A to a more expensive level of control B would be taken if

$$-\frac{X_B - X_A}{S_B - S_A} \leq \alpha$$

Examples of application of this step by step procedure have been published relating to the control of release of radioactive effluents (4) (5) (6).

22. When exposures from a given source or practice can be regarded as composed of contributions of subsystems, each requiring appropriate protection measures, optimization implies that

$$\sum_j (X_j + \alpha\, S_j) = \text{minimum}$$

where X_j is the cost of protection of sub-system j, S_j is the collective effective dose equivalent commitment resulting from sub-system j when its cost of protection is X_j, and α is the monetary value per unit collective effective dose equivalent.

23. Optimization procedures in this situation can be complicated. In one case, however, the constraining functions in the optimization procedures can be readily established, namely when the sub-systems j are independent, in the sense that the control in one of them does not influence the collective effective dose equivalent commitments from the others (4). In this case, differentiating the objective function with respect to each S_j and making each result equal to zero, the following set of equations are obtained for j = 1, 2, ... n

$$\frac{dX_j}{dS_j} + \alpha = 0$$

because for all X_i and S_i where $i \neq j$, the derivatives are equal to zero ($\frac{dX_i}{dS_j} = 0$ and $\frac{dS_i}{dS_j} = 0$), due to the independence of the sub-systems.

24. As individual annual doses should not exceed the operational limit, a further set of equations (limit equations) are obtained (4)

$$f_j (S_j) \leq L$$

It follows from both sets j of equations that the optimization of control can be obtained by optimizing each independent sub-system taken separately. Similarly, the optimization for the combined exposures from several installations at a given site can be obtained by optimizing separately the protection at each installation, provided the condition of independence applies.

25. In cases where the sub-systems are not independent, optimization procedures can be difficult. The protection to be optimized can conceptually be divided into sub-systems while the exposed group can be conceived as composed by sub-groups. After establishing the Objective functions, Constraining functions and Limit equations, if the number of sub-systems and sub-groups is small, the solution can be obtained analytically (7). However, in most cases, the number of variables will not be too large and programming or direct search methods will have to be used (8).

26. A word of caution is necessary presenting the quantitative techniques of optimization. It should be recognized that optimization of radiation protection, as optimization in engineering in general, is basically an intuitive process (8). The quantitative techniques discussed above are a substantial aid to the process of optimization, but are not the complete process itself.

4. JUSTIFICATION

27. The justification of a proposed practice or operation involving exposure to radiation could be determined by consideration of the

advantages and disadvantages to ensure that there will be an overall net advantage from the introduction of the practice. Justification assessments would be required to decide the introduction of a given practice or to select one among many options. The first type of decision is really a particular case of the second, one of the options being not to change the present situation.

28. The decision among several options, the first being not to introduce any new practice, could conceptually be based on a cost-benefit analysis, as indicated in paragraph 2. The basic notion in the application of cost-benefit analysis to such decisions is very simple: a course of action is taken if the resulting net benefit exceeds those of the next best alternative, and not otherwise. Calling the options $i = 1, 2, \ldots n$ and noting with $i = 0$ the decision to introduce no change, then the options would be increasingly justifiable at increasing positive values of the net benefit B_i

$$B_i = (V_i - V_o) - (P_i - P_o) - (X_i - X_o) - (Y_i - Y_o)$$

where the symbols have the same meaning than in paragraph 2.

29. The justified option, B_j, would then be such that

$$B_j = \max (B_i)$$

In practice, the existence of intangible costs and benefits in many cases makes the analysis subjective. However, relative assessments comparing the justification of alternative procedures are simpler, because the same gross benefit is involved. It is apparent from the equations, that in the very simple case of only two options, differing only in the level of protection, the justification assessment becomes identical to optimization.

30. Acceptance of a practice or the choice between practices will depend on many factors, only some of which being associated with radiation. The role of radiation protection in justification procedures is to ensure that the radiation detriment is taken into consideration, and that the comparisons between practices are made after having applied the procedure of optimization to each of them.

5. REFERENCES

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