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ASSIGNING A VALUE TO TRANSBOUNDARY RADIATION EXPOSURE
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FOREWORD

The present Safety Series document is a new step in the continuous effort by the IAEA to implement the 1982 Edition of the Basic Safety Standards for Radiation Protection (Basic Safety Standards), Safety Series No.9, jointly sponsored by the International Labour Organisation, the World Health Organization, the OECD/Nuclear Energy Agency and the IAEA. The objective of the publication is to recommend the minimum value which should be assigned to the unit collective dose in differential cost-benefit analysis for the purpose of optimizing radiation protection of sources having transboundary significance.

Some practices involving the use of ionizing radiation may give rise to radiation exposures beyond the borders of the country in which they are carried out. An example of this is the routine release into the environment from nuclear fuel cycle facilities of radionuclides which are subsequently dispersed across national boundaries or indeed globally. Control of such releases should be governed by the system of dose limitation recommended by the International Commission on Radiological Protection (ICRP) and incorporated into the Basic Safety Standards (BSS).

The BSS require inter alia that all individual doses delivered by a source should be summed to obtain the collective dose commitment for determining the health detriment from the source. For facilitating comparison among alternative control options with the purpose of optimizing the protection through cost-benefit analysis techniques, the value of the detriment has to be presented in the same units as the protection efforts (which are commonly measured in terms of a cost). The BSS recommend a constant (known as ‘alpha’) to be applied to the collective dose commitment for assigning a monetary value to the health detriment. Therefore, alpha is usually expressed in monetary units per collective dose units.

This practice has sometimes been criticized as being unethical, because it might be taken to imply a monetary valuation of a human life. However, it should be emphasized that the Basic Safety Standards clearly state that they do not place a monetary value on human life. In the BSS there is no limit on the cost of protection to keep exposures within the recommended dose limits. It is only suggested that, in any further reduction in exposure, economic and social factors should be taken into account so as to ensure the best use of available resources in bringing about that reduction. Moreover, recent ICRP recommendations on cost-benefit analysis in the optimization of radiation protection indicate that, although cost-benefit analysis techniques require the valuation of the change in life expectancy of unknown individuals, no value is assigned to identified individuals. The factor alpha represents in fact the maximum amount
allocated by society to avoid a unit collective dose, and its magnitude determines the attainable level of radiation protection. As a recent report from a study group of the Holy See's Pontifical Academy of Sciences pointed out, it has nothing to do with a valuation of human lives but is a device for conserving lives. It contributes to society's acceptance of a level of radiation protection which is the highest possible without conflict with other legitimate needs and duties of society.

Competent authorities in a number of countries have assigned a value to alpha for optimization purposes and, inevitably, there has been a certain variation, reflecting different judgements and available resources. In order to reduce the problems arising from the use of different national valuations of the international component of the cost of health detriment, the ICRP has indicated that some internationally acceptable minimum limit for the value of alpha could be selected and adopted for application to this component. When applied to other countries, this minimum value should not be lower than that applied within the source country. To follow up this recommendation, the Agency convened an Advisory Group meeting with participants from thirteen Member States and three international organizations. This meeting considered a draft prepared by consultants and produced the final text published in the present Safety Series document.

The IAEA is particularly grateful to the World Health Organization for its involvement in this project.
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1. SCOPE

1.1. The International Commission on Radiological Protection (ICRP) has provided a system of dose limitation for the control of radiation exposures [1]. This system comprises three basic requirements: justification of a practice involving radiation exposure, optimization of protection measures, and limitation of individual doses. The system is fully described in the Basic Safety Standards for Radiation Protection: 1982 Edition¹ (IAEA Safety Series No. 9), jointly sponsored by the International Atomic Energy Agency, the International Labour Organization, the Nuclear Energy Agency of the OECD and the World Health Organization [2]. The present document contains guidance on the application of the Basic Safety Standards with regard to the particular problem of using differential cost-benefit analysis in the optimization of radiation protection in the case of transboundary radioactive pollution.

2. INTRODUCTION

2.1. Some practices may give rise to radiation exposures beyond the frontiers of the country which carries out those practices. The most notable example is the dispersion of radionuclides released routinely to the environment from nuclear fuel cycle facilities. Transboundary pollution — which can sometimes even be global in extent — is not confined to radioactive substances, but can also be caused by chemical discharges such as the sulphur oxide that results from the combustion of fossil fuels [3]. However, the better knowledge that is available on the environmental pathways to man in the case of radioactive pollution, and the use of the linear, non-threshold, dose-response relationship postulated by ICRP mean that the transboundary component of radiation exposures and its associated detriment can be quantified in a way which is not generally possible for chemical pollutants.

2.2. In establishing regulations concerning the application of the ICRP system of dose limitation, competent national authorities should apply some constraint to ensure that any transboundary component of exposure is given appropriate consideration in the determination of the necessary discharge limitation.

¹ Referred to hereinafter as ‘the Basic Safety Standards’.
3. OPTIMIZATION OF RADIATION PROTECTION

3.1. The guidance that is provided in this document relates to the second basic requirement of the ICRP system of dose limitation, namely optimization of radiation protection. Optimization of radiation protection is synonymous with what is sometimes referred to as ‘ALARA’ – the principle that all exposures should be kept as low as reasonably achievable, economic and social factors being taken into account. This optimization can be achieved through a number of methods, one of which – differential cost-benefit analysis – has been recommended by ICRP and is discussed in detail in ICRP Publication 37 [4]. The following paragraphs briefly describe the principle of this analysis.

3.2. The assumption is used by ICRP that the stochastic component of radiation health detriment, i.e. cancer and hereditary harm, is proportional to the collective effective dose equivalent commitment (here called the ‘collective dose’). This component is the only objective health detriment recognized at radiation doses below the ICRP dose limits.

3.3. For the purposes of differential cost-benefit analysis, a monetary ‘cost’ $Y$ has to be assigned to the radiation detriment. Under the proportionality assumption, with $S$ as the collective dose and the proportionality constant $\alpha$ as the monetary value assigned to the unit collective dose, the cost of the objective health detriment $Y_\alpha$ may be expressed as:

$$Y_\alpha = \alpha S$$

3.4. Publication 37 of ICRP [4] identifies a further component of the radiation detriment, referred to as the ‘non-objective health detriment’. This component, which would include factors such as anxiety and risk aversion, may be particularly relevant when individual dose limits are approached. Use of this component would add to the cost of the detriment a term $Y_\beta$ which may have a functional relationship to the magnitude of individual doses and their distribution.

3.5. The objective of quantitative cost-benefit analysis considered here for the purpose of radiation protection is to minimize the sum of the actual protection cost $X$ and the cost assigned to the residual radiation detriment ($Y = Y_\alpha + Y_\beta$) at the protection level $W$ that is achieved. This is illustrated in Fig. 1, for the case where $Y_\beta = 0$. The effect of adding a beta term will be similar to increasing the value of alpha: it will always lead to improved protection.

3.6. Figure 1 shows how protection is improved as higher values of alpha are used, i.e. the minimum of the $X + Y$ curve moves to the right. It should be noted that use of the ICRP principle of limitation of maximum individual dose alone, without any consideration of collective dose, is equivalent to assuming that $\alpha = 0$. Because of the characteristic shape of $X(W)$ (which illustrates the principle of
VARIABLE DESCRIBING RADIATION PROTECTION, W

FIG. 1. Illustration of the principle of cost-benefit analysis in the optimization of radiation protection: W is a variable describing the level of protection (e.g. retention efficiency, thickness of protective barrier) beyond that required to meet the dose limits; X is the cost of protection; Y is the cost assigned to radiation detriment (Y = aS, where S is the collective dose); and α is the monetary value assigned to the unit collective dose. (Y', Y'' and Y''' are the three values of Y corresponding to particular alpha values of α', 2α' and 3α'.)

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diminishing returns), successive increases in the value of alpha have a rapidly decreasing effect on the value of W that gives the minimum for X + Y. This means that the use of even a small value of alpha may be expected to result in the achievement of a substantial portion of the total reduction possible in residual radiation detriment.

3.7. It is beyond the scope of this document to consider any aspects of radiation protection optimization other than that of choosing the appropriate value of alpha for transboundary exposures resulting from normal operation of facilities involving releases of radioactive material. Therefore, the weights to be given to doses due to random events such as accidents are not discussed.

4. INTERNATIONAL CONSIDERATIONS

4.1. It is worth emphasizing that, as is clearly stated in both the Basic Safety Standards and ICRP Publications 26 and 37, all contributions to the collective dose which are influenced by optimization of the protection of a given source must be included in the assessment of the collective dose S for use in the alpha...
term ($Y_\alpha = \alpha S$). However, it is conceivable that different costs might be assigned to the collective dose contributions inside and outside a country through the use of different values of alpha. If that were done, the alpha term would become

$$Y_\alpha = \alpha_n S_n + \alpha_t S_t$$

where $n$ and $t$ stand for 'national' and 'transboundary', respectively.

4.2. One basic recommendation made in this document is that the monetary value assigned to the unit collective dose for the purposes of costing transboundary collective doses should be no less than the value used for the national collective doses, i.e.

$$\alpha_t \geq \alpha_n$$

National authorities may also, for various reasons, choose a value of $\alpha_t$ higher than $\alpha_n$ in order to further reduce the total collective doses attributable to their practices.

4.3. Since differential cost-benefit analysis is only one of several possible methods of optimization, some authorities may select a method which does not require specification of a value for alpha. However, the general principle should still prevail: policies and criteria for protecting populations outside national borders from releases of radioactive substances should be at least as stringent as those for protecting the population of the country in which the releases occur.

4.4. The adoption of the recommendation that $\alpha_t \geq \alpha_n$ is not by itself sufficient to ensure an acceptable level of protection for transborder populations. A problem could arise if a country, acting on the basis of justifiable national economic and social considerations, were to assign a very low (or even zero) value to $\alpha_n$. Unless some additional requirement were introduced, the same low value might then also be used for the transborder component. It is therefore also recommended that there be an additional restriction on the choice of $\alpha_t$, through the establishment of a minimum value $\alpha_{t_{\text{min}}}$. In the following sections, certain socio-economic considerations underlying the choice of the recommended minimum value and certain implications of its use are discussed.

### 5. ASSIGNING A VALUE TO ALPHA

5.1. The problems of assigning a cost to the health impact of practices, and of putting a value on the benefit to society of improved health protection and the elimination of premature deaths are not confined to radiation protection. The general principles are discussed in standard texts [5, 6] and the particular case of radiation protection is treated by ICRP [4] and elsewhere [7–13].
5.2. Economists and others concerned with the deployment of resources throughout the whole field of public health and safety have developed a number of methods for assessing the value or cost to society of loss of life expectancy. These methods include calculations of the loss of economic output and of associated costs such as medical care, determination of the willingness to pay to avoid loss of life expectancy, calculations of values implied by previous control decisions not based on quantitative consideration of detriment, court compensation awards, analogies with insurance premiums, and assessments based on the allocation of national income to health protection. Some of these approaches have been reviewed by ICRP in the context of radiation protection [4]. Several of them appear to give implied values to the loss of healthy life of the same order of magnitude [14] as the 'human capital' method described in this document; however, in some cases much higher values are implied.

5.3. For the present purpose of obtaining the minimum monetary value of the objective health detriment, it would not be consistent to use methods that give valuations which include both the alpha and beta terms. This rules out methods based on extracting implied values from previous decisions and court compensation awards. Insurance premium analogies are also thought to be inappropriate because insurance payments are based on a different rationale. Thus, methods that would appear to be useful are those based on a direct calculation of the loss of economic output and medical costs, on willingness to pay or on allocation of resources.

5.4. It is recognized that the method based on direct calculation of the loss of economic output—the 'human capital' approach—may, depending on the detailed economic structure of a given society, imperfectly reflect the economic effect of loss of life expectancy in that society. However, no more satisfactory measure is readily available.

5.5. It may be calculated that the expected loss of healthy life attributable to a radiation dose of 1 man·Sv, averaged over a large population, is about 0.4 man-years. This result is based on the following assumptions:

1. The average loss of healthy life from one case of radiation-induced lethal cancer is of the order of 15 years [15];
2. The loss resulting from one case of a hereditary disease that causes a severe handicap is of the order of 30 years [16];
3. The risk factor for induction of fatal cancer is $1.25 \times 10^{-2} \text{ Sv}^{-1}$ [1];
4. The risk factor for induction of severe hereditary harm in all generations is $8 \times 10^{-3} \text{ Sv}^{-1}$ [1].

Strictly speaking, the collective effective dose equivalent is a measure only of the lethal cancers and of the severe deleterious hereditary effects over the first two generations. However, ICRP has stated [17] that in most cases of external
exposure or of exposure to mixtures of radionuclides the use of the effective dose equivalent would not significantly underestimate the total detriment. On this basis, the human capital approach would give a minimum value of alpha which would be:

$$\alpha_{\text{min}} \ [\text{US$}/\text{man} \cdot \text{Sv}] = 0.4 \ [\text{man-years}/\text{man} \cdot \text{Sv}] \times I \ [\text{US$}/\text{man-years}] + C \ [\text{US$}/\text{man} \cdot \text{Sv}]$$

where I is the per caput Gross National Product (GNP) and C is the cost of additional medical care per man-sievert.

5.6. It is shown in Annex A that the value of I ranges from about a few hundred US dollars per man-year in countries with a low standard of living, up to about US$10 000 (in 1981 dollars) per man-year for the most developed countries. If a calculation is made for $\alpha_{\text{min}}$ on a worldwide basis using the equation given in para. 5.5 above, the value for $\alpha_{\text{min}}$ is about US$1000 per man-sievert. This ignores the value of C, which varies from one country to another but is usually small compared to the per caput GNP. The regional variations can be quite large, with $\alpha_{\text{min}}$ (in 1981 dollars) estimated at US$200 per man-sievert for parts of Asia and as high as US$5000 per man-sievert for North America. Because of this wide variation, it is recognized that to recommend a value for $\alpha_{\text{min}}$ applicable for the whole world would have different implications for different countries. This question is discussed in Section 6.

5.7. The last of the methods mentioned in para. 5.3, namely allocation of resources, has been developed for the purposes of this document to illustrate the approximate magnitude of an upper bound for alpha, and is described in Annex B. It is based on a consideration of the resources available for investment in health and safety. Obviously, in a short time perspective only a small portion of the GNP can be used for protection since most of it is required for other beneficial uses, such as providing food, clothing, shelter and medical care. The selection of the appropriate portion to be used for protection depends on many assumptions. One is that equal efforts should be devoted to the various means of reducing loss of healthy life, including radiation protection. On the other hand, the upper bound is somewhat less arbitrary. Arguments given in Annex B indicate that the value of alpha selected for a developed nation is likely to be somewhat less than an order of magnitude higher than that resulting from the human capital calculation.

5.8. The 'willingness to pay' method mentioned in para. 5.3 rests on the actual experience available concerning the willingness to pay to avoid loss of healthy life,
both within and beyond national boundaries. The practice of radiation protection gives some examples:

1. A value of US $10,000 per man-sievert has been adopted in Argentina for optimization of radiation protection to be applied to that part of the collective dose which is influenced by the protection option, national as well as transboundary.\(^2\)

2. A value of US $20,000 per man-sievert has been judged by the Nordic radiation protection authorities (Denmark, Finland, Iceland, Norway and Sweden) to be appropriate for good radiation protection. This applies to the national \(\alpha_n\) as well as to the transboundary collective dose. The authorities have also recognized that marginal values between US $5,000 and US $20,000 per man-sievert may be inferred from reasonable protection measures not explicitly based on cost-benefit assessments [18].

3. A value in the range of US $10,000 to US $20,000 per man-sievert can be inferred from the United States regulations that limit releases of global radioactive pollutants from the nuclear fuel cycle, since these regulations are based on a limiting range of values of US $250,000 to US $500,000 per cancer death or serious genetic effect averted [19].

The three examples for moderately to highly developed countries fall within a range of 2–10 times the lower bounds given by the human capital calculation for these countries. This is not inconsistent with the method based on allocation of resources described in para. 5.7.

5.9. Although it will always be possible to do calculations of the types described in Annexes A and B, the quantification of loss of life expectancy from predicted health effects and the estimation of economic effects such as the loss of income or output involve considerable subjectivity and many sources of uncertainty. Therefore, such calculations should be regarded only as providing one type of input to decisions as to what level of resources should be allocated to optimization of radiation protection involving transboundary exposures. It should be recognized that these calculations are not the only point of reference. The main function of the calculations may be considered to be the provision of a data base on the basis of which a judgement can be made about \(\alpha_{t\min}\).

5.10. On the basis of the above information, it is recommended that \(\alpha_{t\min}\) should be US $3,000 per man-sievert (at 1983 prices). It is anticipated that national authorities in affluent countries would find it appropriate to use substantially higher values for \(\alpha_n\) and, consequently, also for \(\alpha_t\).

\(^2\) Official communication to the IAEA (1983).
6. LIKELY IMPACT OF ADOPTION OF A MINIMUM INTERNATIONAL VALUE OF ALPHA

6.1. The above recommendation could have two different types of impact: one is broadly political, while the other concerns the influence that the choice of values for $\alpha_{t\min}$ could have on particular decisions about levels of radiation protection.

6.2. As discussed in Section 5, there is no established international reference point on which to base judgements about $\alpha_{t\min}$. The recommendation given above should be recognized for what it is: a valuation made by a group of experts as to what should be the minimum value to be used to cost transboundary collective doses in optimization procedures. In a number of countries, optimization of radiation protection is carried out with substantially higher values than those implied by $\alpha_{t\min}$; it is based on a higher value of $\alpha_t$ and in some cases includes an additional beta term. However, it would be a misinterpretation of this document to use the present recommendation on the value of $\alpha_{t\min}$ for transboundary exposures as an argument for a reduction in the level of ambition for radiation protection. The value selected is a minimum value; the choice of $\alpha_{t\min}$ for this particular application carries no implication about values to be used for exposures within a country.

6.3. Conceptually, there could be situations where the present recommendation would have negative consequences for a developing country, apparently requiring it to spend more on radiation protection than it could reasonably afford, given other pressures on its finite resources. However, it is believed that this effect would be extremely unlikely because the recommended value is deemed to be sufficiently low to prevent such effects.

6.4. In order to give some idea of the likely impact of the recommendations in this document on particular decisions, two examples of calculations are given in Annexes C and D. In the example discussed in Annex C, which deals with optimization of carbon-14 retention, the national authorities concerned have decided to choose a value for $\alpha_n$ of US $10,000 per man-sievert, with $Y_B$ being zero. The value of $\alpha_t$ must therefore also be taken as US $10,000 per man-sievert to satisfy the recommended requirements. This results in treatment with a decontamination factor of 100 as the optimum choice. The use of the minimum value of $\alpha_t$ would have resulted in the adoption of a decontamination factor of 50. With $\alpha_t = 0$, no decontamination would be used. Annex D deals with the conclusions of an expert group of the Nuclear Energy Agency of the OECD which examined possible methods for retaining krypton-85 that for an $\alpha_t$ of US $3000 per man-sievert, no retention would be indicated while for $\alpha_t \geq$ US $10,000 per man-sievert, retention with a decontamination factor of 100 would be the optimum choice.
7. SUMMARY AND RECOMMENDATIONS

7.1. As a basic principle, policies and criteria for radiation protection of populations outside national borders from releases of radioactive substances should be at least as stringent as those for the population within the country of release.

7.2. For establishing the cost of the objective health detriment in cost-benefit analysis for optimization of radiation protection, this principle will have the following consequences:

\[ \alpha_t \geq \alpha_n \quad \text{provided that} \quad \alpha_n \geq \alpha_{t\text{min}} \quad \text{otherwise} \quad \alpha_t \geq \alpha_{t\text{min}} \]

where \( \alpha_n \) is the value of the unit collective dose used by national authorities for exposures within their country, \( \alpha_t \) is the value used outside their borders, and \( \alpha_{t\text{min}} \) is the recommended minimum value of \( \alpha_t \).

7.3. The value recommended for \( \alpha_{t\text{min}} \) is US $3000 per man-sievert at 1983 prices. It is anticipated that national authorities in affluent countries would find it appropriate to use substantially higher values for \( \alpha_n \) and consequently also for \( \alpha_t \).

7.4. In the assessment of the collective dose for use with the alpha factor, all the dose contributions which are influenced by the protection variable being optimized must be included. In performing this summation, no weights should be assigned to take account of the distribution of individual doses in space and time. However, the summation could become invalid if extremely uncertain collective dose contributions were included, and therefore careful consideration should be given to the exclusion of such contributions from the summation. It should also be pointed out that optimization assessments should be based on best estimates of the different collective dose contributions.

7.5. If national authorities assign additional values to other components of the detriment in the optimization of radiation protection, for example by using a beta term, or by optimizing by means other than cost-benefit analysis, the basic principle given in para. 7.1 must always apply.
Annex A

ASSESSMENT OF A VALUE FOR ALPHA USING THE 'HUMAN CAPITAL' APPROACH

The basis for the calculation of alpha is given in ICRP Publication 37 [4], and calculations have been carried out by various authors [9, 10]. The calculation in this Annex has deliberately been made simple in order to provide an approximate value not too sensitive to detailed assumptions.

The calculation is based on the mean per caput GNP I, derived from the World Bank Atlas [20] and shown in Table A.I. This gives the world average per caput GNP in 1981 as US $2740. The corresponding per caput GNP for Asia would be about US $400 and for North America about US $13 000. To estimate the value of $\alpha$ using the ‘human capital’ approach (see para. 5.4), annual costs of additional medical care have to be added. However, if the cost of medical care C is not more than about US $10 000 per case, and if the induction rate for lethal cancer is $10^{-2}$ Sv$^{-1}$, then the component of that cost to be included as C is only US $100 per man-sievert. This is small compared to the societal income component (0.4 I).

On this basis, the mean value of $\alpha_{\text{min}}$ based on the worldwide per caput GNP is about US $1000 per man-sievert with a range from about US $200 per man-sievert for Asia to about US $5000 per man-sievert for North America.
### TABLE A.1. WORLD GROSS NATIONAL PRODUCT AND POPULATION (1981)
(Taken from the 1983 World Bank Atlas [20])

<table>
<thead>
<tr>
<th>Region</th>
<th>GNP per caput (US $)</th>
<th>GNP(^a) (US $10^9)</th>
<th>Population (10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>12,680</td>
<td>3,222</td>
<td>254</td>
</tr>
<tr>
<td>Japan</td>
<td>10,080</td>
<td>1,186</td>
<td>118</td>
</tr>
<tr>
<td>Oceania</td>
<td>8,620</td>
<td>198</td>
<td>23</td>
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<tr>
<td>Indonesia</td>
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<td>Middle East</td>
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<td>39</td>
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<tr>
<td>USSR(^b)</td>
<td>4,040</td>
<td>1,067</td>
<td>268</td>
</tr>
<tr>
<td>South America</td>
<td>2,160</td>
<td>520</td>
<td>240</td>
</tr>
<tr>
<td>Central America including Mexico</td>
<td>1,930</td>
<td>220</td>
<td>114</td>
</tr>
<tr>
<td>Africa</td>
<td>810</td>
<td>383</td>
<td>473</td>
</tr>
<tr>
<td>China</td>
<td>300</td>
<td>300</td>
<td>990</td>
</tr>
<tr>
<td>India</td>
<td>260</td>
<td>177</td>
<td>690</td>
</tr>
<tr>
<td>South-east Asia</td>
<td>653</td>
<td>265</td>
<td>406</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>56,213</strong></td>
<td><strong>11,540</strong></td>
<td><strong>4,217</strong></td>
</tr>
<tr>
<td><strong>Total GNP/total population</strong></td>
<td><strong>2,740</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\) The GNP figures do not include a number of countries for which data were not available.

\(b\) 1979 data.
Annex B

BOUNDARY CONDITION FOR ALPHA, USING AN APPROACH BASED ON A PORTION OF AVAILABLE NATIONAL RESOURCES

When national resources are apportioned to satisfy human needs, priority is generally given to the basic needs such as food, shelter, clothing and elementary medical care. Less vital necessities for protecting life and health are given a priority which depends on socio-economic conditions in the country concerned. This Annex discusses the limits set by the national income in the short term to those means which are available for protection but which do not contribute immediately to saving life or health. On the assumption that resources for radiation protection are similar to those available for protection against other sources of risk, this implies a limitation to the value of alpha.

This Annex discusses first the question of the number of lives available to be saved. Then an upper limit to the average expenditure per life saved is defined.

How many years of life or lives can be saved?

We consider first how to answer this question for an industrialized country with a high standard of living and hygiene. In Sweden, the mean age in the general population is 37 years for men and 39 years for women. The mean expected remaining life is 37.5 years for men and 41 years for women. The figure of 38 years can thus be taken as an approximate value for the mean expectancy of remaining life. The annual death rate is 92 000 in a population of 8.32 million. Obviously, this is the upper limit of the number of lives that can be 'saved' annually. The deaths from sources of risk of the type mentioned above will only be a fraction of the total number of deaths.

Crude estimates indicate that perhaps one-fifth of these may be savable by prevention of cancer, accidents, suicide, etc., and by better treatment of, for instance, cancer and diabetes. This would mean about 300 000 savable man-years per year, out of the 8.32 million, corresponding to an associated increase in life expectancy of at most 3 years. Actual experience indicates that there are only small differences in life expectancy between industrialized countries, thus not contradicting the hypothesis that it would be unlikely that a very substantial increase in life expectancy could be achieved in a highly industrialized country such as Sweden.

What limit can be set to alpha, given limited resources?

Over a short time period the Gross National Product G is approximately constant, and constitutes an absolute upper limit to the amount that could
possibly be spent for life-saving measures. At this limit, the maximum amount spent to save one man-year is $G/N$, if all loss of life expectancy incurs equal unit cost. In reality, some spread of the cost is unavoidable. Since considerable efforts are already spent in industrialized countries for life-saving, the spread is, however, assumed to be small and the average extra cost approximately equal to the marginal cost. Since saving one man-sievert implies saving 0.4 years, the maximum value of alpha is limited to $\alpha_{\text{max}} = 0.4 \cdot G/N$ if radiation protection is to be treated as is protection in other areas. With the numerical estimate for Sweden given above, we obtain

$$\alpha_{\text{max}} = 0.4 \times 100 \times 10^9 / 300 000 \quad \text{(US $/\text{man} \cdot \text{Sv})}$$

or roughly

$$\alpha_{\text{max}} = 130 000 \quad \text{(US $/\text{man} \cdot \text{Sv})}$$

Over a period of 10 years, it would be conceivable, although very unlikely, that all of the economic growth of Sweden, perhaps 10% of the GNP, might be spent for protective measures. This amount would correspond to all that is presently spent on health. With such an assumption, we would get

$$\alpha_{\text{max}} = \text{US $13 000 per man-sievert}$$

Since the human capital method would give for Sweden

$$\alpha_{\text{hc}} = \text{US $5000 per man-sievert}$$

we obtain $\alpha_{\text{max}} = 2.6 \alpha_{\text{hc}}$ (where ‘hc’ stands for human capital).
Annex C

AN EXAMPLE OF OPTIMIZATION OF CARBON-14 RETENTION AT A NUCLEAR POWER PLANT

This example is based on a study reported by Beninson and González [21]. In 1981 a licence was approved by Argentina's regulatory authority for the construction of the Atucha II nuclear power plant. One of the requirements made by the authority for granting the construction licence was the inclusion, in the design of the reactor, of a system for controlling the release of carbon-14. This type of reactor, which uses natural uranium and is moderated and cooled by heavy water, produces substantially more carbon-14 than light water reactors.

One step in the study was to consider whether the decontamination factor needed to comply with the upper bound required by the local regulations was high enough not to warrant further reduction of the release; for this purpose, an optimization of protection was performed. Compliance with the optimization requirement implies a balance between the marginal value of the remaining collective dose commitment and the marginal cost of the control system between different control options. For the Atucha II reactor, two control options that have been considered transform the gaseous radiocarbons into solid carbonate, with decontamination factors of 50 and 100 (see Table C.I). Although the non-control option would have been automatically disregarded because it does not comply with the upper bound requirement of the regulations, this option was included in the optimization assessment for the purpose of conceptual illustration.

Even if retention measures were applied, carbon-14, because of its long half-life, would eventually be released into the environment since the carbonates lose their retention properties with time. Therefore, the marginal collective dose commitment between options is equal to the difference between the incomplete collective dose commitments (from the time of the immediate release as a result of the practice up to the time of the future release from the disposed carbonates) since the two integral tails cancel each other. The time of retention of the carbonate-controlling option is considered to be of the order of 10,000 years if proper disposal of the carbonate compounds is assumed. Therefore, in spite of the very long half-life of carbon-14, only the incomplete collective dose commitments over 10,000 years need to be evaluated for optimization assessments.

The activity of carbon-14 available for release during the lifetime of Atucha II was estimated to be of the order of $10^{14}$ Bq. If the selected control option were non-retention of carbon-14 (option A), this amount of activity would be released into the environment. The 10,000 years incomplete collective dose commitment, in this case, is estimated to be $3 \times 10^4$ man · Sv. If retention with decontamination factors of 50 (option B) or 100 (option C) were introduced, the commitments would be $6 \times 10^2$ man · Sv and $3 \times 10^2$ man · Sv, respectively.
TABLE C.1. CONTROL OPTIONS FOR USE IN THE OPTIMIZATION ASSESSMENT AT THE ATUCHA II NUCLEAR POWER PLANT IN ARGENTINA

<table>
<thead>
<tr>
<th>Option A (no retention)</th>
<th>Option B (decontamination factor of 50)</th>
<th>Option C (decontamination factor of 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S (man • Sv)</strong></td>
<td>3 X 10^4</td>
<td>6 X 10^2</td>
</tr>
<tr>
<td><strong>X (US $)</strong></td>
<td>0</td>
<td>11.5 X 10^6</td>
</tr>
<tr>
<td>∆X (US $)</td>
<td>11.5 X 10^6</td>
<td>2.9 X 10^6</td>
</tr>
<tr>
<td>∆S (man • Sv)</td>
<td>~3 X 10^4</td>
<td>3 X 10^2</td>
</tr>
<tr>
<td>∆X (US $/man • Sv)</td>
<td>380</td>
<td>~9700</td>
</tr>
</tbody>
</table>

The control system involves two steps. In the first, the effluents from the coolant and moderator circuits of the reactor are transformed into an appropriate gaseous compound. Through a catalytic procedure, all monoxides and deuteromethanes are expected to be recombined to carbon dioxide (CO₂). In the second step, the gas is transformed into carbonate by means of a gas scrubber with an alkaline-scrubbing barium hydroxide solution (Ba(OH)₂) in a column. The substance formed is barium carbonate (BaCO₃) dispersed in water, and it is separated by filtering. The filters can be managed as standard solid wastes and will be incorporated into a matrix material for ultimate disposal in an appropriate repository.

For decision making in optimization assessments, the Argentine authorities use a figure of US $10 000 per man-sievert as the monetary value of the unit collective dose commitment. Option C is the one which satisfies the procedure of optimization.

It should be stressed that the Argentine regulations give the same value of alpha for local and global exposures, and discounting is not applied to costs relating to exposures to be experienced in the future.

It is interesting to see what would be the effect of using other values of alpha. If the same methodology were used, but with the proposed international minimum for alpha (US $3000 per man-sievert) instead of the US $10 000 per man-sievert used by the Argentine authorities, option B would best meet the optimization requirement.
ANNEX D

AN EXAMPLE OF OPTIMIZATION OF KRYPTON-85 RETENTION AT A REPROCESSING PLANT

An expert group of the OECD Nuclear Energy Agency has examined possible methods for retention of krypton-85 produced at a fuel reprocessing plant during the fuel dissolution stage [22]. They also assessed the costs of the retention methods and the collective doses resulting to both local and global populations. These data have been used as the basis for a further examination of optimization procedures [14].

On the basis of data from these studies, the costs and collective dose estimates shown in Table D.I were obtained. Option A corresponds to no retention of krypton-85, while options B and C (variations of cryogenic distillation techniques) imply decontamination factors of 10 and 100 respectively.

The release of krypton-85 may cause high individual doses to the local population, which could be a sufficient reason to retain it, but the present example does not take this factor into account.

### TABLE D.I. RETENTION OPTIONS FOR KRYPTON-85

<table>
<thead>
<tr>
<th></th>
<th>Option A (no retention)</th>
<th>Option B (decontamination factor of 10)</th>
<th>Option C (decontamination factor of 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (man • Sv)</td>
<td>260</td>
<td>26</td>
<td>2.6</td>
</tr>
<tr>
<td>X (US $)</td>
<td>0</td>
<td>2.2 × 10^6</td>
<td>2.4 × 10^6</td>
</tr>
<tr>
<td>(\Delta X) (US $)</td>
<td>2.2 × 10^6</td>
<td>2 × 10^5</td>
<td></td>
</tr>
<tr>
<td>(\Delta S) (man • Sv)</td>
<td>234</td>
<td>23.4</td>
<td></td>
</tr>
<tr>
<td>(\Delta X) (US $/man • Sv)</td>
<td>9400</td>
<td>8500</td>
<td></td>
</tr>
</tbody>
</table>

It can be seen from Table D.I that if an alpha value of US $3000 per man-sievert is used, no retention would be indicated. At alpha values exceeding about US $10,000 per man-sievert, decontamination by a factor of 100 would be the best alternative.
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LIST OF PARTICIPANTS

Bengtsson, G. National Institute for Radiation Protection, P.O. Box 60 204, S-104 01 Stockholm, Sweden
Beninson, D. Comisión Nacional de Energía Atómica, Avenida del Libertador 8250, 1429 Buenos Aires, Argentina
Bush, W.R. Atomic Energy Control Board, Martel Building, 270 Albert Street, Ottawa, Ontario K1P 5S9, Canada
Lindell, B. National Institute for Radiation Protection, P.O. Box 60 204, S-104 01 Stockholm, Sweden
(Chairman)
Namestek, L. Czechoslovak Atomic Energy Commission, Sleszká 9, Prague 2, Czechoslovakia
Paretzke, H.G. Institut für Strahlenschutz, Gesellschaft für Strahlen- und Umweltforschung, Ingolstädter Landstrasse 1, D-8042 Neuherberg, Federal Republic of Germany
Richardson, A.C.B. Office of Radiation Programs, ANR-460C, United States Environmental Protection Agency, Washington, DC 20460, United States of America
Subbaratnam, T. Health Physics Division, Bhabha Atomic Research Centre, Trombay, Bombay 400 085, India
Sztanyik, L.B. National Institute for Radiobiology and Radiation Hygiene, Pentz Károly u. 5, H-1211 Budapest XXII, Hungary

PARTICIPANTS DESIGNATED BY INTERNATIONAL ORGANIZATIONS

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)
González, A.J. Division of Nuclear Energy and Safety, P.O. Box 100, A-1400 Vienna, Austria

NUCLEAR ENERGY AGENCY OF THE OECD
Ilari, O. Division of Radiation Protection and Waste Management, 38, boulevard Suchet, F-75016 Paris, France

UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION (UNSCEAR)
Silini, G. Vienna International Centre, P.O. Box 500, A-1400 Vienna, Austria
WORLD HEALTH ORGANIZATION (WHO)

Clark, M.J. National Radiological Protection Board, Chilton, Didcot, Oxfordshire OX11 ORQ, United Kingdom

Jammet, H. CEA, Centre d'études nucléaires de Fontenay-aux-Roses, B.P. 6, F-92260 Fontenay-aux-Roses, France

Wei, L. Laboratory of Industrial Hygiene, China National Centre for Preventive Medicine, 2 Xinkang Street, Deshengmenwai, Beijing, China

OBSERVERS

Bouville, A. CEA, Centre d'études nucléaires de Fontenay-aux-Roses, B.P. 6, F-92260 Fontenay-aux-Roses, France

Godas, T. National Institute for Radiation Protection, P.O. Box 60 204, S-104 01 Stockholm, Sweden

Tscherlovits, M. Atominstiut der Österreichischen Univeristäten, Schüttelstrasse 115, A-1030 Vienna, Austria

SCIENTIFIC SECRETARY

Daw, H.T. Division of Nuclear Energy and Safety, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria

FIRST CONSULTANTS MEETING

Vienna
29 November - 3 December 1982

Beninson, D. Comisión Nacional de Energía Atómica, Avenida del Libertador 8250, 1429 Buenos Aires, Argentina

Coppee, G.H. Occupational Safety and Health Branch, Working Conditions and Environment Department, International-Labour Office, CH-1211 Geneva 22, Switzerland

Ilari, O. Division of Radiation Protection and Waste Management, Nuclear Energy Agency of the OECD, 38, boulevard Suchet, F-75016 Paris, France

Jammet, H. CEA, Centre d'études nucléaires de Fontenay-aux-Roses, B.P. 6, F-92260 Fontenay-aux-Roses, France

Komarov, E. Division of Environmental Health, World Health Organization, Avenue Appia, CH-1211 Geneva 27, Switzerland
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