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Optimization of Radiation Protection in the Control of Occupational Exposure

International Atomic Energy Agency, Vienna, 2002

OPTIMIZATION OF RADIATION PROTECTION IN THE CONTROL OF OCCUPATIONAL EXPOSURE

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OPTIMIZATION OF RADIATION PROTECTION IN THE CONTROL OF OCCUPATIONAL EXPOSURE

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FOREWORD

One of the three main principles on which protection against ionizing radiation is based is the principle of the optimization of radiological protection. The principle of the optimization of protection was first enunciated by the International Commission on Radiological Protection in the 1960s. A principal requirement for the optimization of protection and safety has been incorporated into the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Basic Safety Standards) from the first edition in 1962 up to the current (1996) edition. The principle of optimization, that all reasonable efforts be made to reduce doses (social and economic factors being taken into account), necessitates considerable effort to apply in practice.

The requirement of the Basic Safety Standards to apply the principle of optimization applies to all categories of exposure: occupational, public and medical. The categories of public and medical exposure are rather specific and are covered in other publications; this Safety Report concentrates on the application of the principle to what is probably the largest category, that of occupational exposure. This Safety Report provides practical information on how to apply the optimization of protection in the workplace. The emphasis throughout is on the integration of radiation protection into the more general system of work management, and on the involvement of management and workers in setting up a system of radiation protection and in its implementation.

This Safety Report was drafted and finalized in three consultants meetings held in 1999 and 2000. The draft was sent for review and comment to a number of experts, which yielded valuable comments from a number of reviewers whose names are included in the list of contributors to drafting and review. Particular acknowledgement is made of the contributions made to the preparation of this Safety Report by J. Blaikie, C. Schieber and G.A.M. Webb. The IAEA officer responsible for the preparation of this Safety Report was M. Gustafsson of the Division of Radiation and Waste Safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

For many years optimization has been one of the three principles of radiation protection. It is introduced in the Safety Fundamentals publication Radiation Protection and the Safety of Radiation Sources [1] and is a basic element of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [2]. A Safety Guide (Safety Series No. 101), Operational Radiation Protection: A Guide to Optimization [3], was published in 1990 and was intended to provide practical guidance on the application of the dose limitation system to operational situations. That Safety Guide was related to the previous version of the BSS, however, and did not cover the application of the optimization principle to all situations, including design. It was therefore decided to prepare this Safety Report, which supercedes Safety Series No. 101, to give more practical advice that covers the whole range of applications to occupational exposure.

Although the requirement for optimization applies to all categories of exposure — occupational, medical and public — the application to non-occupational exposures in the latter two categories is rather specific and adequately covered in publications in those fields. In the case of public exposure a major aspect is optimization in waste management, especially for discharges to the environment and for the disposal of solid wastes, which is treated in detail in publications in the Radioactive Waste Safety Series. The optimization of intervention measures to protect the public in the event of an accident has been covered in a Safety Guide (Safety Series No. 109 [4]) in which generic optimized intervention levels are derived. Other aspects of public exposure are exposures to natural radiation, particularly radon, which is largely covered in the BSS. For medical exposure the relevant application of optimization is set out for diagnostic and therapeutic procedures in a specialized Safety Guide on Radiological Protection for Medical Exposure to Ionizing Radiation [5], and the practical aspects will be elaborated in a series of publications jointly sponsored by the IAEA and four other international organizations. It has therefore been decided to focus this Safety Report on the first category: occupational exposure.

In carrying out an optimization study from the point of view of radiological protection, other hazards that may be associated with radioactive materials (e.g. biological and chemical hazards) or with the process operations (e.g. electrical and mechanical hazards) also have to be borne in mind and may indeed affect the final decision on the optimum course of action.

The development of the recommendations of the International Commission on Radiological Protection (ICRP) have been taken into account in preparing this Safety Report, especially the publications that relate specifically to optimization [6, 7] and the more recent report [8] that deals with the radiation protection of workers. More specific publications by the OECD Nuclear Energy Agency (OECD NEA) [9], by the Commission of the European Communities [10] and from the United States National Council on Radiation Protection and Measurements [11] have also provided some valuable concepts and examples of applications.

Three related Safety Guides prepared jointly by the IAEA and the International Labour Office provide guidance on fulfilling the requirements of the BSS with respect to occupational exposure [12–14]. The Safety Guide that gives general advice on the development of occupational radiation protection programmes [12] sets out the essential elements of the optimization procedures and has formed the basis on which this Safety Report elaborates.

1.2. OBJECTIVE

The main objective of this Safety Report is to supplement the general principles and guidance on optimization given by the ICRP, in the BSS and in the Safety Guides with more practical information on how to apply optimization in the workplace. It is stated in Ref. [12] that the primary responsibility for the optimization of the protection of workers lies with the operating management of the organizations in which they work. The primary target audience for this Safety Report is thus the managers who have responsibility for controlling the types of work done and the resulting occupational exposures. This includes those directly responsible for radiation protection, for example radiation protection officers (also called health physics managers or health physics officers). An equally important target audience is those managers responsible for production or other aspects of an organization such as financial control, for whom safety should also be an integral consideration. These persons should also be involved in the development and implementation of the results of optimization decisions. As stated below, the successful application of the ideas in this Safety Report also depends upon the commitment and involvement of the workers who are being protected, so they, or their representatives, are an important further target audience. This Safety Report should also be useful to regulatory authority personnel in clarifying how operators can comply with a regulatory requirement for optimization.

1.3. SCOPE

This Safety Report covers the background to, and the practical aspects of implementation of, a programme for the optimization of radiation protection in the control of occupational exposure. This kind of programme is often referred to as an

ALARA (as low as reasonably achievable) programme. The term ‘occupational exposure’ means “All exposures of workers incurred in the course of their work, with the exception of exposures excluded from the Standards and exposures from practices or sources exempted by the Standards” (Ref. [2], Glossary). It applies to all aspects of facilities, including design, the carrying out of operations and decommissioning. It covers all types of occupational exposure, including that from the medical and industrial uses of radiation, and exposure to natural radiation at work as well as exposure in the nuclear power industry. Although in principle it also covers the reduction of potential exposure, and some of the examples given in this Safety Report show measures for the reduction of probability as well as the magnitude of doses, the more formal optimization techniques are not yet fully applicable to the trade offs between dose and risk reduction. As noted earlier, optimization in emergency situations is covered in other publications, and so it is not part of the scope of this Safety Report.

1.4. STRUCTURE

The general process for the optimization of radiation protection is presented in Section 2. Carrying out this process requires several steps, which are described in Sections 3 to 6. The starting point is an assessment of the initial situation, whether it is a new design or a current operation, as described in Section 3. Section 4 elaborates the various possible methods and approaches that could be taken to reduce doses. The evaluation of the possible courses of action that lead to an ALARA plan and the implementation of the plan is dealt with in Section 5. Some brief conclusions are presented in Section 6. Throughout this Safety Report examples of applications of the procedures are described. Although every effort has been made to draw these examples from all areas of applications of radiation, most studies that have been reported come from the nuclear power industry, so inevitably most of the examples also come from that sector.

2. OPTIMIZATION PROCESS

The current form of the framework for radiation protection, including the concept of the optimization of radiological protection[1], can be traced back to a

[1] In this Safety Report the term ‘optimization’ is taken to mean the ‘optimization of radiological protection’.

publication of the ICRP in 1965, but was stated in Publication No. 26 in 1977 [15] in a form that remained similar in Publication No. 60 from 1991 [16] and in the BSS. This wording in the BSS is:

> "In relation to exposures from any particular source within a practice, except for therapeutic medical exposures, protection and safety shall be optimized in order that the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures all be kept as low as reasonably achievable, economic and social factors being taken into account, within the restriction that the doses to individuals delivered by the source be subject to dose constraints" (Ref. [2], para. 2.24).

Optimization is an essential part, and in practice the most important part, of a system of dose limitation because reliance on dose limits is not enough to achieve an acceptable level of protection. Dose limits represent the lower boundary of a region of unacceptable doses and risks. Doses just below the limits can therefore only be tolerated if nothing reasonable can be done to reduce them. In most situations, however, something can be done to reduce them, and protection then enters the optimization regime that is the subject of this Safety Report.

As noted above, dose limits are usually too high to be a useful level for placing an upper boundary on a particular optimization study. Indeed, in most situations of occupational exposure the dose limit is largely irrelevant. To provide a boundary to optimization the ICRP has introduced the concept of dose constraints, which are expressed as individual doses, as are the dose limits, but which are a source related constraint on the range of options considered in the optimization of protection for that particular source. Dose constraints need to be used prospectively in optimizing protection in planning and executing tasks, and in designing facilities or equipment. They should therefore be set on a case by case basis that takes into account general trends but that is consistent with the specific characteristics of the exposure situation, and they should preferably be set by management in consultation with the workers involved. A useful basis would be an analysis of the dose distributions in operations of a particular type that are felt to be well managed. A dose constraint could be set towards the upper end of such a distribution of doses. A recent study on the setting of dose constrains [17] has concluded that there seems to be some areas of work where constraints are unlikely to be appropriate, either owing to doses being low or because there are problems in applying the concept itself. However, a study by the OECD NEA found them to be useful in many situations [18]. Within the nuclear sector the use of constraints may be most appropriate in the planning of new facilities where there is a well defined planning stage and there is sufficient information on dose distributions to inform the selection of constraints. This would also apply in the medical sector in the planning of radiotherapy, including brachytherapy, nuclear medicine and radiography facilities, and to some industrial operation, such as fixed radiography facilities.

In contrast to dose constraints, which is a prospective tool, there is often a need for some kind of indicator of performance during operations. It would not be appropriate for this to be a limit or constraint, so the term investigation level is used. Investigation levels need to be specific to the facility or operations concerned and will therefore usually be set by management at the local level, taking into account the results of the optimization study that has been performed. Investigation levels should be set in terms of measurable quantities such as individual doses, intakes, dose rates or contamination levels. Investigation levels will often be a component of an ALARA plan. A review of the situation to determine the causes and, if necessary, to initiate further measures to control exposures should be prompted if an investigation level is exceeded.

Another type of reference for use during operations is a collective dose target. This is similar to an investigation level in that approaching or exceeding it will trigger an investigation, so it can be a useful indicator to management of the overall performance of a job in comparison with the predictions of an optimization study or comparison with best practice in other similar situations. Collective dose targets will also often form part of an ALARA plan.

The ICRP has recognized that ‘keeping all exposures as low as reasonably achievable, economic and social factors being taken into account’, ‘optimization of protection’ and ‘ALARA’ are identical concepts within the ICRP system [19]. Because it is widely recognized worldwide, the acronym ALARA is used in this Safety Report where it seems appropriate.

The optimization of protection is an idea of broad application. At the top level it covers the organizational structure needed to enable the correct allocation of responsibilities. It can be used for decisions at all levels, from simple day to day operational problems to major analyses of different types of plant design, and it should be applied in all areas of occupational radiation protection, including the medical uses of radiation, exposure to natural radiation and in general industry as well as in the perhaps more publicized area of the nuclear power industry. The optimization idea should also in principle apply to procedures designed to prevent or mitigate the consequences of incidents in the workplace that could lead to radiation exposure. To do this it needs to take account of the probabilities of such events and of their consequences, but as noted earlier the techniques to do this are not yet developed so these aspects are not treated in this Safety Report.

The fundamental role of optimization is to bring about a state of thinking in everyone responsible for the control of radiation exposures, such that they are continuously asking themselves the question ‘Have I done everything that I reasonably can to reduce these radiation doses?’. Clearly, the answer to this question is a matter of judgement because it is not a question that can be answered in the same sense as the corresponding question about dose limits, ‘Have I ensured compliance with the dose limits?’. If the doses received by a worker are monitored and the sum of these over the designated period is less than the limit, then the answer to the question of compliance with the dose limit is ‘yes’. In the case of the optimization question, partly because optimization is largely a prospective operation, there is no such clear cut technical answer that does not require the application of judgement. Demonstration of compliance with an optimization requirement in regulations must therefore also be a matter of judgement. In this Safety Report the matters to be taken into account in reaching such a judgement are explained.

In modern industry, economic pressures have made productivity and cost competitiveness essential considerations. Companies have therefore adopted a global approach to work that stresses the importance of approaching jobs from a multidisciplinary team perspective and of following jobs completely through the stages of conception, design, planning, preparation, implementation and follow-up. This approach to jobs is what is broadly termed work management. It has much in common with the systematic approach to optimization recommended in the Safety Guide on Occupational Radiation Protection (Ref. [12], para. 4.6), which says

> “Optimization of protection is a process that begins at the planning stage and continues through the stages of scheduling, preparation, implementation and feedback.”

In most cases optimization has to achieve a balance by taking into account the needs for dose reduction, the needs to maintain production and the costs involved. Ref. [12] recommends the implementation of the process of optimization through work management. Because the reduction of doses through work management is often accomplished by measures that improve the working conditions, the goals of increasing efficiency and optimizing radiation protection can often be achieved together. It may even be the case that this overall improvement in work output and dose reduction can be achieved at no net financial cost if the savings through the improved efficiency outweigh the cost of the protection measures.

A wide range of techniques is available to assist in optimizing radiation protection. Some of these techniques are drawn from operational research, some from economics and some from engineering. The techniques available include, but are not confined to, procedures based on cost–benefit analysis; it is these procedures that were discussed in detail in the first major ICRP report, published in 1983 [6]. The ICRP has, however, stated the importance of recognizing that other techniques, some quantitative, some more qualitative, may also be used in the optimization of radiation protection. It is these techniques that were developed in a later more general report [7], which was published in 1989, and endorsed in the most recent recommendations in 1991 [16]. The techniques are described in Annex I.

The primary responsibility for optimization lies with the management of a facility. The commitment of senior management, often expressed through a policy statement, is an essential prerequisite for the successful introduction or continuation of an ALARA programme. A further important early step in preparations for the implementation of an ALARA programme through work management is to create in the organization concerned the appropriate management structures and to allocate responsibilities. This should be complemented by broad programmes to raise awareness and provide the necessary basic education. Other more technical measures to optimize protection should be subjected to analysis, for which a systematic procedure is helpful. This approach to the organization and control of work is not unique to optimization but is part of normal effective management. Such a procedure is shown in Fig. 1 and consists of the following steps.

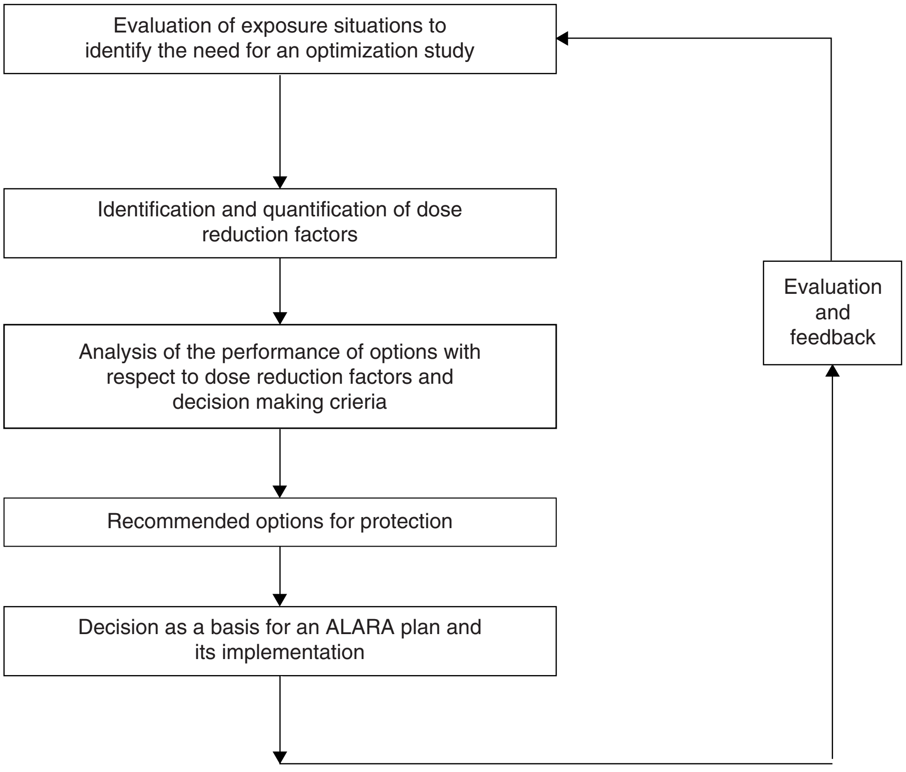

FIG. 1. The optimization procedure.

1. The evaluation of exposure situations to identify the need for an optimization study. To do this it is often helpful to use comparators or examples of good practice. These may be comparisons with other similar facilities in databases such as the Information System on Occupational Exposure (ISOE) [20] or the reviews of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [21] or they may be dose constraints for the type of work set by management or by a regulatory authority. In general it is prudent to carry out a systematic review of all exposure situations. For example, in design and planning operations consideration should be given to lower dose situations if there are a number of workers exposed frequently or for long periods. In some cases it will be obvious that a particular high dose job is a candidate for improvement.

2. The identification and quantification of the dose reduction factors to be considered during the optimization study. In this next step all of the means by which doses may be reduced are identified. These factors include global means, which can apply to all operations, and those specific to the optimization of protection in particular jobs. Combinations of various means can be referred to as options for improving protection.

3. The analysis, which may be qualitative or quantitative, of the performance of the options with respect to each of the dose reduction factors and the decision making criteria set up in advance. The overall objective of optimization deals with the radiation exposure of the workforce. To assess this the individual dose distribution, especially the maximum individual doses, is one of the key factors. As it is also important to take into account the number of workers exposed to particular levels of dose, the collective dose to the workforce is a necessary factor. Collective dose here means the sum of the doses predicted or actually received by a specified workforce either in a period of time, such as a year or month, or in carrying out a specific job. The relevant criteria provide guidance, quantitative or qualitative, of what is acceptable or desirable for one of the factors. For example, the individual dose constraint is a criterion of one type, a specified monetary value of unit collective dose is another criterion. These criteria can be used with other less quantified inputs in deciding on an overall ALARA plan and in respect of specific jobs.

4. The generation of a recommended optimum protection option. With account taken of the results of the analysis, including the costs of all types and effectiveness of the various means of dose reduction, one or a few options are likely to emerge as optimum.

5. The final decision, which is then the basis for an ALARA plan and its implementation. By means of techniques to involve management, workers who may affect the situation and those workers who will be affected in the decision making process, the appropriate combination of general means to optimize protection and to approach particular jobs can be identified by taking into account the proposed optimum options. This can then be formed into an ALARA plan for implementation.

In one sense it is this procedure that is the important practical embodiment of the optimization concept. The procedure, which can be applied to both design and operational situations, is aimed at clarifying the problem under consideration so that all available means to reduce doses are considered in identifying the main radiological protection options, together with their costs and any other relevant factors. The steps in the procedure are expanded in the subsequent sections of this Safety Report.

In the carrying out of an optimization study it is necessary to involve other groups. These include particularly the workers who have direct knowledge of the situation being studied and can therefore make suggestions as to the relevant factors and how they might be modified, and other management groups having control of finances or involved in the situation from a production viewpoint who can specify constraints of a financial or technical nature or who may be able to make suggestions for improvement from a wider perspective.

The concrete output of an optimization study will be an ALARA plan with both short and longer term objectives that may be termed ALARA goals. These goals could be set, for example, in terms of maximum individual doses and collective dose targets. The plan may also include investigation levels to be used during the operation of the plan to trigger scrutiny if there are deviations from the predicted dose patterns. In implementing the plan the need to communicate both the reasons for changes and the expected benefits is important. The involvement of the groups referred to above in the development of the plan will have the additional benefit of involving those who have to implement it. In the implementation phase it will be necessary also to emphasize the responsibilities for his or her own improved protection of every individual involved and for improvements in the protection of work colleagues.

During the implementation of the plan there should be monitoring of the changes in the indicators and opportunity for feedback so that when there is a further review in the future the database for that review is clear and complete.

3. ASSESSMENT OF EXPOSURE SITUATIONS

Occupational exposures situations range from simple (e.g. a medical technician administering a chest X ray) to complex (e.g. tasks involving several hundred workers in the refuelling and maintenance outages of a nuclear power plant). In Ref. [12] it is noted that a radiation protection programme has to be well adapted to the situation concerned. To ensure this the first step is to perform an initial radiological evaluation of the practice or installation in question. The purpose of this initial evaluation is to describe, as precisely as necessary, the situation involving occupational exposures. It is recommended that this evaluation includes, for all aspects of operations [12]:

"(a) an identification of the sources of routine and reasonably foreseeable potential exposures;
(b) a realistic estimate of the relevant doses and probabilities;
(c) an identification of the radiological protection measures needed to meet the optimization principle."

This Safety Report is concerned with optimization, and the evaluation procedures described here focus on working towards an ALARA plan within an overall radiation protection programme.

In a generic approach, whatever the degree of complexity, there are two main levels of assessment. The first consists of a global evaluation of the exposure to identify the major areas for improvement and to check the overall effectiveness of an optimization programme if one already exists. The second deals with a detailed analysis of specific jobs in order to examine the factors that contribute to the associated doses and determine the appropriate means that could be implemented for the reduction of the doses.

3.1. GLOBAL EVALUATION OF THE EXPOSURE SITUATION

Before starting any optimization process it is necessary for management to carry out an initial radiological evaluation to obtain a generic overview of the exposure situation for which it is responsible, evaluate the evolution of the exposures and identify the main areas for improvement.

3.1.1. Design stage

At the design stage of a new facility (e.g. a nuclear power plant, research laboratory, radiography room in a hospital) or in preparing for a new operation (e.g. the dismantling of a facility, a major plant modification), a global evaluation of the exposure situation should be carried out to determine if the individual dose constraints [17, 18] and the collective dose targets (if any have been established) are satisfied (see the example in Section 3.1.1.1). These two elements, which are source related, reflect in a generic sense what can be regarded to be achievable relative to the results obtained in similar facilities or exposure situations at the national or international level: this is described in Section 2.

At the stage of the first characterization of the future exposure situation, the main indicators to be looked at are the level of the collective dose and the distribution of individual doses (i.e. the number of workers exposed as a function of the ranges of individual levels of dose). The data for this type of global overview is generally collected on an annual basis. These indicators are obtained through a generic description of the major radiological jobs that are planned to be performed in the facility concerned. This description is based on a rough estimate of the frequency of the jobs performed, their duration, the dose rates and the possible number of workers exposed.

A comparison of the indicators with the individual dose constraints and collective dose targets identifies the design modifications that have to be made before construction in order to meet the objectives. Design modifications can also be carried out to improve conditions at existing facilities. An evaluation must therefore be started as early as possible in the design process in order to keep a maximum of flexibility for potential changes in the original design. The process of the optimization of protection is then implemented by means of a second and more detailed assessment of all the jobs, to reduce the doses as much as reasonably achievable below these levels of dose constraints or targets, taking into account social and economic factors (see the example in Section 3.1.1.2). A reassessment of the situation should be planned on a periodic basis.

3.1.1.1. Example 1: Individual dose constraints and indicators

A number of organizations have established dose constraints and indicators for design purposes, such as for:

— Power reactors.
  - Individual annual dose.
  - Annual collective dose per unit installed capacity.
  - Average annual individual dose in the workforce.

— Reprocessing operations.
  - Individual annual dose.

— Radiation protection advisers.
  - Individual annual dose.

— Research laboratory technicians.
  - Individual annual dose.

3.1.1.2. Example 2: Design of a major facility

This example presents the main results of a detailed optimization study performed at the design stage of a facility for the treatment and conditioning of radioactive waste from the nuclear industry. The facility is composed of two main units: a fusion unit (for metal wastes) and an incineration unit (for solid or liquid combustible and non-combustible wastes). The different steps of the study are the following.

(a) First evaluation of the exposure situation with rough estimates (excluding maintenance jobs):

— Collective dose: 0.83 man·Sv/a.
— Number of individuals exposed: 63 exposed workers.
— Average individual level of dose per year: 13.2 mSv.

(b) The optimization study decided upon the following objectives:

— Individual dose constraint: 15 mSv/a, to eliminate any option that would lead to an annual individual dose greater than this value.
— Reducing the level of individual and collective doses, with priority given to the highest levels of individual doses.
— Eliminating all exposure situations where the use of respiratory protective equipment would be necessary for more than two hours.

(c) Second evaluation of the exposure situation with a more realistic hypothesis and a more precise description of the work steps; to be used as a reference for the optimization study:

— Collective dose: 0.77 man·Sv/a.
— Number of individuals exposed: 88 exposed workers.
— Average individual level of dose per year: 8.75 mSv.

(d) Optimization study: identification of the protection options, quantification of their effectiveness and the cost of options, and selection of the optimal options (mainly the improvement of shielding and development of remote tools). Final results were the following:

— Collective dose: 0.53 man·Sv/a.
— Number of individuals exposed: 93 exposed workers.
— Average individual level of dose per year: 5.7 mSv.

Table I shows the distribution of individual doses both before and after the optimization study. The main point of this example is to show that the implementation

TABLE I. DISTRIBUTION OF INDIVIDUAL DOSES BEFORE AND AFTER AN OPTIMIZATION STUDY (EXCLUDING MAINTENANCE JOBS)

	Number of workers per annual individual dose range			
	<5 mSv/a	5–10 mSv/a	10–15 mSv/a	15–20 mSv/a
Fusion unit				
Before optimization	15	13	8	5
After optimization	36	7	3	0
Incineration unit				
Before optimization	8	14	15	10
After optimization	9	37	1	0

of protection options enables the reduction of both the annual collective dose and the average individual dose, even though the number of exposed individuals had to be slightly increased in order to satisfy the individual dose constraint.

3.1.2. Operational stage

In the operation of a facility the responsible managers (including radiation protection officers) should perform regular assessments (for example on an annual basis) of the global exposure situation of the facility, in order to:

— Evaluate the generic tendencies;
— Check any possible deviations;
— Monitor the effectiveness of the radiation protection programme, including the ALARA plan;
— Identify the main areas for improvement;
— Determine future goals for doses.

The main indicators used for this purpose are usually annual trends of the total operational collective dose and distributions of annual individual doses (see the example in Table II). When the various jobs that characterize the exposure situation can be grouped into different categories, and when several types of workers (e.g. labourers, technicians, engineers) are concerned, the indicators can be detailed for each category of job and type of worker to allow a better analysis of the situation. These can be analysed alone to evaluate the trends in occupational exposures of the facility concerned and to compare them with trends at similar facilities (at the national or international level) for benchmarking purposes.

TABLE II. EXAMPLE 3: ANALYSIS OF TRENDS IN DOSE INFORMATION FOR OCCUPATIONALLY EXPOSED WORKERS IN INDUSTRIAL RADIOGRAPHY FOR THE YEARS 1990–1996

	1990	1992	1994	1996
Collective dose (man·Sv)	3.8	4.1	2.6	2.5
Mean dose (mSv)	1.4	1.6	1.3	1.6
Number with doses greater than 15 mSv	37	22	29	9

Note: The data for the years 1990–1992 prompted a review of the work practices in industrial radiography that resulted in reductions in both the individual and collective dose.

In addition to the global evaluation of trends, it is also necessary to check whether the specific dosimetric goals, dose constraints, etc., set as part of the optimization process, are met (e.g. the maximum annual individual doses, the collective dose per year or per category of job).

Further evaluation of the less quantifiable indicators of the effectiveness of a radiation protection programme is also necessary (see the example in Section 3.1.2.1). From a work management perspective, these less quantifiable indicators include:

- — The commitment towards the optimization of radiation protection of all the persons whose functions are directly or indirectly related to the management of radiation jobs, from the top management to the individual workers who are exposed to the radiation;
- — The level of knowledge of these individuals concerning the various dosimetric goals (e.g. educating the workers in the field on such subjects as annual or task related goals);
- — The involvement of workers and management in the studies of radiation protection optimization;
- — The quality of the information systems and the effectiveness of information dissemination;
- — The continuing education of workers regarding changes and improvements in optimization processes.

In making all these periodic evaluations, managers have to be aware that even if the exposure situation seems satisfactory at the facility level and in comparison with similar exposure situations in other facilities, it may still be possible (or necessary) to reduce the doses further. The optimization process is a dynamic process, the results of which need always to be further questioned.

3.1.2.1. Example 4: Involvement of personnel in the process of evaluating exposures

The process of evaluating exposures should include in some way all workers who are occupationally exposed. Essential to the evaluation process is a core team of people who provide the overall direction and planning of the exposure process. It is likewise necessary that this core team be comprised of personnel outside the radiation protection department. Although the chairperson (or facilitator) of this core team may be a member of the radiation protection department, the majority of the members should be representatives of work groups other than the radiation protection department.

3.2. JOB SPECIFIC EVALUATION AND ANALYSIS

3.2.1. Prior evaluation of all radiation jobs

In addition to the periodic assessment of the global exposure situation, the planning of all jobs that might lead to an occupational exposure should include, as early as possible before the job starts, a broad evaluation of the levels of collective and individual doses directly associated with the job. This evaluation should be performed by the responsible work group, that is the group that will actually be carrying out the job, in close co-operation with and with assistance from the radiation protection group. It needs to be based on a technical description of the job and be associated with an evaluation of the radiological conditions in which the work will be performed.

The objectives of a prior evaluation of the exposure levels of jobs can include:

- — Obtaining the elements needed to identify and elaborate on job related dosimetric goals;
- — Identification of the exposure conditions (i.e. where, when and how the workers are exposed);
- — Bringing together the appropriate individuals in both the responsible work group and the radiation protection group;
- — Identification of the jobs to be further analysed to improve radiological protection.

The level of evaluation, planning and review should be commensurate with the estimated doses associated with the jobs concerned. It may be useful to determine a reference value in terms of the individual or collective doses such that if the exposure estimate of a job were to exceed this predetermined value a further formal analysis would be conducted to identify the dose reduction options, followed by a senior management review of the evaluation and planning efforts. The categories of job and related ALARA reviews proposed by the National Council on Radiation Protection and Measurements for nuclear power plants is given in the example in Table III [11]. The reference value is likely to be different for each type of facility.

The selection of jobs needing further detailed analyses can also be made through a comparison with results previously obtained for the same type of job (either in the facility concerned or other comparable facilities), which may reveal that a better performance can be obtained. In this case not only the collective dose trends but also the evolution of the main parameters that contribute to exposures (i.e. the dose rates, duration of the job and number of workers) are significant. The analysis of the collective dose trends associated with repetitive jobs (e.g. routine annual maintenance jobs) or similar jobs performed in different places should be complemented by an analysis of the ambient dose rate as well as the exposure workload (the total time spent by an entire team in a work area, measured in person-hours) to detect the possible changes in radiological or technical conditions from one job to another (see the example in Section 3.2.1.1). This type of analysis may show that an increase in the collective dose is not due to the poor performance of a job but

TABLE III. EXAMPLE 5: COLLECTIVE DOSE CRITERIA TO DETERMINE THE LEVEL OF A JOB ANALYSIS

Category	Dose estimate	Review
1	<10 man·mSv	By a radiation protection technician as part of a radiation work permit preparation
2	10–50 man·mSv	By a radiation protection technician and radiation protection supervisor
3	50–500 man·mSv	By a radiation protection supervisor and engineer responsible for ALARA planning Dose estimate and planned dose reduction techniques to be documented in a pre-job report to management
4	>500 man·mSv	In addition to the above, review by the plant’s management or an ALARA committee

to an increase of the ambient dose rate (and similarly a decrease in the collective dose due only to a decrease in the ambient dose rate can be offset by an increase of the number of workers exposed or the duration of the exposure).

3.2.1.1. Example 6: Analysis of similar jobs performed successively in different workplaces

This example presents the type of analysis that can be done when looking at the dose trends for a job performed several times by the same team (i.e. the same number of workers) but in different workplaces.

The first step of evaluation usually consists of an analysis of the trend in the collective dose. In this example (see Table IV) it appears that the collective dose for the job is progressively decreasing, which seems to indicate a better performance of the job and an improvement in work efficiency.

However, because the job has been performed in different workplaces, in order to make a true interpretation of the dose trend (Table V) it is necessary to look at the ambient dose rates as well as the exposure workload. Table V shows that, although

TABLE IV. TREND OF THE COLLECTIVE DOSE

	Job sequence				
	1	2	3	4	5
Collective dose (man·mSv)	36	30	24	17	15

TABLE V. INTERPRETATION OF THE DOSE TREND

	Job sequence				
	1	2	3	4	5
Collective dose (man·mSv)	36	30	24	17	15
Ambient dose rate (mSv/h)	0.4	0.3	0.3	0.2	0.1
Exposure workload (person-hours)	90	100	80	85	150

the collective dose for the job is decreasing, the time taken to carry out the job is increasing. The decrease in the collective dose is due to a decrease in the ambient dose rate only. In terms of the optimization of protection, such a result should call for a more detailed analysis of the way the job was performed in order to check for possible mishaps or technical problems that increased the exposure workload.

3.2.2. Analysis of exposure situations for specific jobs in the context of carrying out a detailed study for the optimization of radiation protection

A detailed analysis is a necessary step for performing studies for the optimization of radiation protection (see Fig. 2). It is normally done not only for the jobs identified by global evaluations of exposure but also for all major new work. Moreover, a periodic analysis should be performed for all the radiation related jobs at the facility concerned in order to determine what could be done to reduce the levels of doses (even if the levels of occupational doses associated with these jobs seem satisfactory).

The purpose of these analyses is to identify the possible factors that contribute to the level of doses that could be improved or changed. It should be based on a precise description of all the tasks performed in the job, in radiological, technical and environmental (which equates to a description of the area) terms. This means that detailed information concerning the time of exposure, the number of workers involved, ambient dose rates in the work areas, the use of protective clothing, procedures and tools, and the configuration of the work areas (including ergonomic criteria, the possible position of shielding, scaffolding, materials and tools) need to be obtained. The various groups of workers that interact in the preparation or performance of these jobs and that are directly involved in the identification of the means to reduce exposures need to participate in the collection of data and in the analyses of the jobs.

3.3. HOW TO OBTAIN THE DATA

3.3.1. Facility level and national level

At a facility's internal level one important means of ensuring the efficient assessment of exposure situations is to create a complete information system that enables the collection, analysis and storage of data. As mentioned above, these data are not limited to dosimetric data but are also related, among other factors, to a job's performance and the prevalent work conditions.

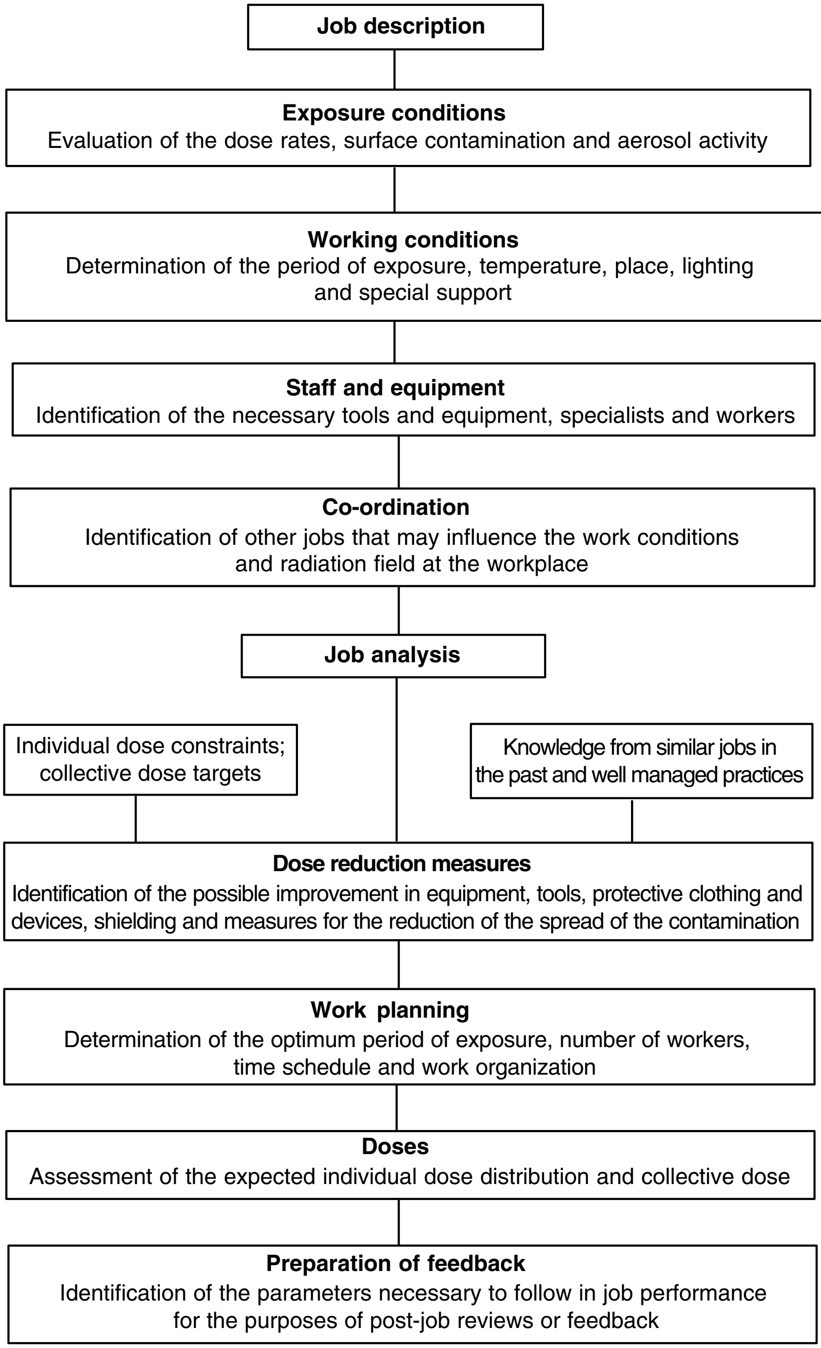

FIG. 2. Analysis of jobs.

The data can be collected directly, either before, during and after jobs are carried out. In some cases the most efficient way to obtain data is to use systematically completed records, completed either by the radiation protection staff or by the job foremen both during and at the end of the work. These records need not be complex: simple record cards may suffice in many cases. In collecting data for repetitive jobs a coherence between the successive collection of data is important for an accurate analysis. In complex exposure situations (i.e. those that involve several sources or several types of job), computer based collection systems, most easily associated with an electronic operational dosimetry system, can be helpful in collecting information.

In some cases, such as at the design stage of a facility or for a new job or when no information is available, it may be necessary to use specific software to facilitate the following:

— Assessments of dose rates and their possible evolution in time;
— Simulations of the planned jobs in their environment;
— Combinations of data from all the planned jobs (for ambient dose rates, the length of time of exposure and the number of workers exposed) at the facility concerned, in order to obtain more generic indicators.

Periodic internal reviews or audits are also useful for evaluations, in particular reviews that concern an assessment of the awareness of workers and other types of human or organizational factors that lead to a poor performance. To obtain a more objective evaluation it can also be useful to ask for an external audit, which can be accomplished, for example, through alternate peer reviews in which two facilities participate in evaluations of one another.

The use of national databases can often be helpful if there is no job related information available to provide an indication of good practice or to identify areas for attention (see the example in Section 3.3.1.1).

3.3.1.1. Example 7: IAEA Regulatory Authority Information System

To support the regulatory authorities in its Member States the IAEA has developed the Regulatory Authority Information System (RAIS), which is being introduced in about 70 countries that receive IAEA assistance. The RAIS system consists of five modules, one of which covers individual dose monitoring. This module provides the regulatory authority with the necessary information on occupational exposure for its monitoring of safe operation. RAIS also provides comparisons with reference levels, such as investigation levels, and with dose constraints and dose limits, and reports on doses that exceed the reference levels.

3.3.2. International level

For some types of exposure situations there exist international databases that group dosimetric information by the types of radiation jobs performed in various facilities.

International data relevant to all types of work can been obtained through the periodically published reports of UNSCEAR on the sources and effects of ionizing radiation [21]. These reports include detailed data on occupational exposures in various sectors of industry and from various types of sources in different countries. The main groups of occupational categories used in the report are nuclear fuel cycle, the medical uses of radiation, the industrial uses of radiation, the natural sources of radiation and defence related activities. Within each group distinctions are made between the major types of practices. For these practices the collected data concern, for each responding country, the number of monitored workers, the total annual collective effective dose, the average annual individual dose and the distribution of the number of workers and of the total collective dose per individual dose range. For nuclear power plants a more specific system has been developed (see the example in Section 3.3.2.1).

3.3.2.1. Example 8: Information System on Occupational Exposure

The field of occupational exposures at nuclear power plants has benefited since 1992 from an international programme called the Information System on Occupational Exposure (ISOE). This programme was launched by the OECD NEA to facilitate the exchange of experience in the management of occupational exposure among utilities and regulatory authorities from around the world. Since 1993 it has been co-sponsored by the IAEA to allow the participation of member countries not in the OECD NEA, and in 1997 the two agencies formed a joint ISOE secretariat.

The ISOE programme includes the management of an international database on occupational exposures and a network that allows the participants to obtain or exchange all types of information that relates to radiation protection in nuclear power plants. At the end of 2000 data from 92% of the world's operating commercial nuclear reactors were included in the ISOE database.

The ISOE provides each member utility with the database, which contains detailed information on the individual and collective doses associated with the major activities performed in and outside refuelling outages, a description of the specific design features of the various reactor types and forms for the feedback of experience from some specific jobs performed by some utilities. An annual report contains an analysis of the data and a summary of the principal events in the participating countries that might have influenced the trends in occupational exposure [20].

4. MEANS OF REDUCING EXPOSURE

4.1. INTRODUCTION

Following the completion of an assessment it may be determined that there is a need to reduce doses and that there is a means by which the reduction can be carried out. The methods for reducing doses cover a broad spectrum, which ranges from simple organizational adjustments to a modification of the design of the facility concerned.

The ways in which exposure can be reduced are presented as singular factors (means) and may be applicable as singular factors. However, a combination of these factors (means) in many situations is likely to be more effective. This section begins with basic, yet essential, means and progresses towards more technical elements.

Not all of these means are necessarily applicable to all situations. There are many options for using them singly or in combination. The use of a combination of these means, and their relative order, should be delineated in an ALARA plan, which is discussed below. The decision of which means are applicable and should be adopted should precede the development of an action plan and is discussed in the next section.

Checklists are useful tools for carrying out the requirements of an optimization programme, and their uses are varied. Among other uses they can be used as an agenda for a job planning or post-job review meeting or can be distributed to workers to provoke thought for a process of information feedback. There are various types of checklist; the type used will likely vary depending upon the type and size of the facility concerned (see the examples in Annex II).

4.2. GLOBAL MEANS OF REDUCING EXPOSURE

4.2.1. Work planning and scheduling

Effective work management is necessary for the optimization and reduction of exposure. Work needs to be managed and planned from the perspective of the specific task, as well as its relation to all the other tasks performed, according to a common goal and schedule. Decisions on when specific tasks are to be performed necessitate the consideration of the radiological conditions prevailing at that given time. There may be a better time to perform the job, in consideration of the radiological conditions, without affecting the schedule for the completion of the job (see the example in Section 4.2.1.1). It is useful to start with a template of the basic work plan and schedule to review the plan for opportunities to adjust the specific time at which a task is scheduled to be performed. The dose averted should be balanced against the duration and cost of the work, with account taken of any impacts that any changes may have on the plan to optimize radiation protection.

Resource management should be considered a part of work management in optimizing radiation protection. Most studies have shown that an increase in the number of workers for a specific job, in order to reduce the workers' individual exposure, will sometimes increase the total duration of the job and result in higher collective exposures than if the job was performed by a small, well trained team. This aspect of work management needs to be carefully reviewed and scrutinized to ensure that the doses are the lowest possible. Time and motion studies and mock-up training can help to identify proper management by determining precisely the workload necessary to perform each step of the job and the right number of workers. These items are discussed in Section 4.3.5.

4.2.1.1. Example 9: Schedule of works according to the evolution of dose rates

When nuclear power plants initially shut down, the dose rates in the vicinity of the shut down cooling system piping and components increase significantly. Work on these systems should therefore be scheduled prior to shutdown or well after shutdown to allow for ion exchange and filtration cleanup as well as for some radioactive decay.

4.2.2. General worker education

A knowledgeable workforce is a fundamental element in any programme for the optimization of protection and control of exposure. Basic radiological training is a requirement for gaining initial access to any radiation area and for performing work in these areas. Training in optimization covers, as a minimum, the basic aspects of time, distance and shielding, and how these basic elements relate to the optimization of protection (see the example in Section 4.2.2.1). Requalification training at prescribed intervals is generally a requirement. Requalification training normally includes a reminder of the initial basic worker training and a review of new regulations, guidance documents and work protocols relevant to the concept of optimization.

A basic understanding of radiation protection is only the first step, however. Workers also need to have a good working knowledge of the environment in which they are working. They need to have an understanding of the basic practices and the principles for radiological work that need to be employed in the specific radiological environments in which they are working (such as radiation areas, high radiation areas, contamination areas and areas of airborne activity). They need also to be trained in practical matters, such as how to dress and undress in protective clothing, wearing hoods and gloves, and so on. Familiarity with the physical surroundings is another prerequisite. Workers need to have details of, for example, entry and exit points so that time spent in radiation areas is minimized, thus reducing exposure. An awareness of general dose rates in the area concerned as well as hot spots and low dose waiting areas has equal importance. This is further explained in Section 4.2.3.

4.2.2.1. Example 10: A software learning program — RADIOR

To explain the optimization of radiation protection a software learning program, RADIOR, has been developed. It includes modules on ionizing radiation, the management of radiological risks and the application of the optimization principle, and a test of the acquired knowledge. While most of the content is generally applicable, the practical example of the application of the optimization principle is taken from the nuclear industry. The development of RADIOR was supported by the IAEA and the European Commission Environment Directorate-General. RADIOR is available on a diskette from the IAEA in English, French, German, Russian, Spanish and Swedish.

4.2.3. Awareness and involvement of workers

Individuals performing tasks in radiation areas can have a large effect on their own exposures. For this reason awareness on the part of workers has an important part to play in reducing doses (see the example in Section 4.2.3.1). This effect on workers' exposures starts with the planning phase of the work to be performed.

Direct involvement in the planning phase provides workers with an opportunity to apply experience and lessons learned to the development of the plan. This allows individuals to become more knowledgeable of the potential risks and to develop a commitment to the plan. Knowledge of both the global and job specific ALARA plans includes familiarity with the goals for both annual and task specific exposure. This improves the attitude and attention to detail that the individual has in the performance of his or her job and leads to a reduction in exposures.

Further reduction in exposures can be gained from the involvement of workers in an in-process evaluation, post-job review and feedback process. Much valuable information can be gained from workers by means of these processes. The forum for the feedback and review process needs to be an open discussion. Workers need to be assured that their input is valued and can benefit the optimization process.

Workers' awareness can be improved in other ways. Signs can be posted in work areas around facilities where they can be easily seen by workers as constant reminders of the potential hazard and the need to minimize exposure. Examples of these signs include ‘Low Dose Waiting Area’, ‘Do Not Loiter In This Area’ and other cautions concerning the potential hazard in handling radioactive material. Information signs such as these are most effective if they are distinctive in size and colour, are recognizably different from other information signs and are specifically recognized as being relevant for the optimization of protection. The use of electronic dosimeters with easy to view displays of current cumulative dose levels and radiation levels are also effective in advising workers of the prevailing radiological conditions. Awareness is further improved by posting the results of radiological surveys at the entrances to rooms in which there is any type of radiological hazard.

Workers should also be made aware that areas with high dose rates are normally subject to some form of access control, either by the use of locks or by requiring a designated person to accompany workers entering the high dose rate area. In addition to the actual procedures, the reason for introducing access controls needs to be explained so that workers are not tempted to circumvent the protection measures through ignorance.

An additional measure that promotes workers’ awareness is the appropriate labelling of radioactive material. While regulations may require certain types of labels that have a minimum of information directly related to the existing radiological conditions, additional information, such as handling instructions or details of the necessary handling tools, further increase workers’ awareness. All labels and signs need to be in the language(s) most familiar to the workers that they are addressed to.

4.2.3.1. Example 11: Mobile industrial radiography

A study was carried out on 700 radiographers who work with mobile industrial radiography equipment. It was found that about 240 of them received annual doses that exceed 5 mSv. Detailed investigations identified the following reasons why the radiographers received doses that were higher than necessary:

— Difficult working conditions,
— A failure to observe the operational procedures set up in compliance with the regulations on radiation protection,
— The use of old equipment.

It was determined that one of the most effective measures to reduce doses would be training and raising the awareness of the workers, which was done with the involvement of both the regulatory authority and the companies employing the radiographers.

4.2.4. Communication

Communication is an essential part of any effort to reduce exposure. Regular communication is necessary between all levels of management, supervisors and the workforce. Workers need to be encouraged to communicate with management either directly or by means of some formal process. Much of this is part of the process of feedback, which is further elaborated in Section 5.3. Equally necessary is the involvement of workers in the development of options for dose reduction and in the consideration of the practicalities that concern their adoption.

4.2.4.1. Example 12: Improving communication by the use of suggestion boxes

Any worker at a facility needs to have available the means to communicate ideas, lessons learned and good practices. One method that can be employed is the use of a simple suggestion form. Suggestion forms and suggestion boxes can be located at various points around a facility. Information to be given on the form should include the concern (i.e. something causing more exposure than necessary), any proposals for dealing with it and the name of the individual who has submitted the form (this is optional). The person charged with responding to the concern should evaluate the problem and any proposed solutions. Whether or not any particular proposal can be acted upon, individuals who submit forms should be sent a written reply that explains the outcome of the evaluation.

4.3. JOB SPECIFIC MEANS TO REDUCE EXPOSURE

4.3.1. Facility and equipment design

The most effective global means of reducing exposure is having an initial design for a facility that takes full account of the requirement to optimize protection. In some modern facilities this goes so far as to eliminate exposure owing to intakes of radionuclides entirely by the use of containment and remote handling, or for a radiotherapy suite to eliminate external exposure by the use of remote operation and shielding. These are extreme examples, but the importance of attention to protection at the design stage cannot be overemphasized. For this reason, those persons involved in designing facilities need to be fully conversant with the consequences of the requirement for optimization.

Another major means of reducing the exposure of workers is through the good design of equipment. The design of equipment needs to take full account of the exposure of the workers who will be using it, and a comprehensive system of quality assurance is necessary to ensure that the construction, operation, maintenance and modification of sources and equipment meet the relevant requirements. The design and its construction needs to take full account of human capabilities.

Design modifications can be an effective permanent means of reducing exposure. Examples include installing permanent shielding in areas where temporary shielding is frequently used (see the example in Section 4.3.1.1). Other types of design modification can improve many aspects of workers' environments by improving access, increasing efficiency and allowing for expedience in job performance. Increased efficiency enhances safety and reduces exposure. Although there is often a tendency to dismiss design modifications owing to their cost, they are effective in reducing exposure at facilities that are already in operation. Design modifications that incorporate the optimization of protection together with improved industrial safety and increased production could both cut costs and reduce exposure. This is an important element of optimization, as it crosses boundaries with other programmes and can lead to improvements in more than one programme.

Design modifications are normally included in the long range component of an ALARA plan owing to the lead time necessary for the requisite engineering and budgeting. Consequently, these issues are initially evaluated simply to determine whether exposure can be reduced. Subsequently, modifications can be fully evaluated in terms of reductions in exposure, feasibility and cost.

4.3.1.1. Example 13: Factors for evaluation in a decision on the need to install permanent shielding

It may be that, as a result of the original design of an installation, temporary scaffolding may frequently be needed (such as for maintenance work on components such as steam generators). Evaluations of the need for permanent platforms instead of temporary scaffolding readily show reductions in doses, as scaffolding does not need to be installed in every refuelling cycle. The doses received in installing the platforms are received only once. Permanent platforms also have other advantages: they are inherently safer and thus represent a reduced risk in terms of industrial safety. Workers can also perform their tasks more efficiently without the bulky safety harnesses necessary on temporary scaffolding. Therefore, an evaluation as presented to management would show the following:

- — Reduced labour costs owing to no need to construct and remove temporary scaffolding,
- — Reduced labour costs as a result of increased work efficiency (less time means less expenditure),
- — Increased industrial safety and increased confidence in industrial safety on the part of workers,

— A reduction in radiation exposure owing to there being no need to construct and remove temporary scaffolding,
— A further reduction in radiation exposure owing to increased working efficiency.

4.3.2. Reducing the time spent in radiation areas

Reducing the amount of time spent in a radiation area will always reduce the exposure (see the example in Section 4.3.2.1), but the time needs to be reduced without the quality of the desired output being compromised. Reductions in exposure are lost if work has to be repeated. Planning is an essential element in reducing the time spent in radiation areas. Good planning of tasks can reduce, by various means, the time spent in radiation areas.

Ensuring that all the necessary tools, supplies and other equipment are available at the job site will reduce delays. Ensuring that instruments are in proper repair and working order will reduce the likelihood that work and testing will need to be repeated. A basic consideration is that of having the proper tools for the specific task being performed. Some tasks may need specially designed tools that can be fabricated at the facility were the work takes place. This is especially helpful because in most cases the individual who designs and fabricates the tool will be the person who will perform the work. This will increase workers' awareness of and familiarity with both the work itself and considerations in optimization.

A workforce that is familiar with the needs of a job can also reduce the number of person-hours spent in a radiation area. Familiarity with the work needs can be achieved through practice tasks or mock-ups (see Section 4.3.5). Furthermore, the use of workers who have performed a task previously will contribute to a time reduction. In this case, however, there is a potential imbalance in doses among workers. Having several workers familiar with the same job is of much greater value than having a single expert. This will also aid in time reduction when the need arises for complex tasks that need more than one or two workers.

The work environment and all the varied forms of protective equipment and clothing can also affect the amount of time necessary to perform a specific task (i.e. worker efficiency). Job planning includes an evaluation of the duration of a job and the consequent dose with and without protective clothing, protective equipment (such as respiratory protection) and engineering controls (such as portable ventilation to reduce the ambient temperature). Consideration needs to be given to the estimated dose associated with setting up any portable equipment as well as to the doses that workers are expected to receive in performing a task. In general it is found that the use of protective clothing increases the time taken to do a job and hence the dose due to external exposure. It will, however, reduce the internal exposure or the probability of internal exposure, for which the estimation of doses is less reliable. The outcome of optimization includes an appropriate choice of protective clothing with all these considerations taken into account.

4.3.2.1. Example 14: Factors that increase exposure time

Poor working conditions might significantly increase the time spent by workers in radiation areas. In a study to quantify the effect on the exposure time of certain working conditions associated with maintenance jobs in nuclear power plants, it was shown, for example, that inadequate lighting of a work area, noisy conditions in areas without the use of audio links between workers or congestion can increase the exposure time by up to 20% over that for work performed with adequate lighting or in an open area.

Analyses of routine maintenance and post-incidental operations in nuclear power plants have shown that mishaps or poor working conditions could increase the exposure time associated with these operations by 20 to 30% on average. The main causes of mishaps were identified as an inadequate preparation of work (e.g. scaffoldings not appropriate for the situation, schedule problems), wrong or malfunctioning tools and lack of training.

The working time and the quality of work may be highly influenced by the use of protective clothing and equipment. A study performed with mock-ups showed that the effect of wearing protective clothing on the working time depends upon the type of protective suit worn and may vary with the type of work to be performed. For example, for precise work performed in a congested area the use of a rubber overall suit with an air supplied hood can increase the working time by up to 30% over that for the same task performed in a cotton overall. For the same task the use of rubber overalls and an air supplied full face mask, which provides the same level of protection against internal contamination but which is much more cumbersome, may increase the necessary working time by up to 65%. This example shows that the selection of protective clothing needs to take into account the ergonomic factors that relate to the tasks to be performed (such as the level of effort, the need for precision or the duration of the task). The use of protective clothing and the working procedure should also be considered in designing the tools to be used.

4.3.3. Reducing the number of workers necessary

The number of personnel involved in a job can be optimized by eliminating the use of unnecessary personnel and using only the minimum number of personnel necessary to complete the task. As with time reduction, this needs to be done without reducing the quality of the desired output and without compromising the safety of personnel. Unnecessary personnel can be defined as those personnel who do not perform any defined task. Personnel who perform observations or tasks that do not necessitate physical contact or immediacy with the component concerned or area in which the work takes place can be removed from the immediate radiation area to an area with a lower level of radiation. These individuals can be called upon to perform their task quickly and can then return to the lower radiation level area. The use of remote video, audio and dosimetric telemetry, if available, can eliminate the need for those workers assigned to observation tasks. Work planning can also help, for example by having a person complete more than one task while in an area or while dressed in the appropriate protective clothing.

4.3.4. Reducing dose rates

Methods for reducing dose rates differ depending upon the application and the environment within the facility concerned. Facilities with piping systems that contain radioactive fluids can have dose rates that change with system conditions and which could lead to high area dose rates around the piping system in general, high dose rates at specific locations (hot spots) or both. These high dose rates can be controlled and minimized and possibly reduced to zero by such methods as applying controls on the system chemistry, filtration, ion exchange and flushing.

Other methods for achieving substantial reductions in dose rates in reactor environments are methods such as improving the water chemistry, modifying shutdown procedures and the use of zinc injection. In the medical area changes in procedures, such as changing from direct to afterloading brachytherapy, can significantly reduce dose rates for workers. These methods are more related to the running of a facility as a whole, but serve to illustrate the importance of the involvement of senior management in the optimization process.

If a room, area or component is highly contaminated the contamination could contribute to the dose rates in the local or general area and result in higher doses to workers. Decontamination of the component or area concerned could reduce dose rates. In order to ensure optimization, the doses received in the decontamination process need to be offset against the doses averted.

Temporary shielding can effectively reduce radiation levels in various applications. All tasks subject to high dose levels need to be evaluated for the effectiveness of installing temporary shielding. An evaluation should be performed to investigate the benefits of installing temporary shielding in terms of reduced dose rates. The basis for this evaluation includes the estimated doses that the workers will receive in performing the job both with and without shielding. The difference between these estimated doses is compared with the doses that would be received in installing and removing the temporary shielding. If the reduction in the doses to be realized by installing the shielding does not exceed the doses received in the installation of the shielding, then the shielding need not be installed. This evaluation should also take into account any possible averted doses that would otherwise have been received in the course of other work being performed in the vicinity of the shielding proposed to be installed.

The design of temporary shielding needs to be carefully considered in order to adapt it as much as possible to the configuration of the work area. In some cases it may be necessary to check that the installation of shielding does not reduce the work space in such a way that it may significantly increase the duration of subsequent work and thus the period of exposure of workers.

In addition to jobs in which doses are potentially high, areas with lower radiation levels but which are frequently accessed should also be evaluated for the use of temporary shielding. Examples of such areas include walkways and other areas of general access where people assemble or through which people pass. These are circumstances in which, although the installation of temporary shielding would seem to be beneficial, it may not be possible to quantify the averted doses. The shielding should be installed as close to the source as is practicable. The closer the shielding is to the source, the more effective it will be at reducing dose rates. It will also minimize the amount of shielding needed.

The use of personal protective equipment is a means of reducing doses that can be considered when other controls cannot reduce doses reasonably. The reduction in efficiency needs to be taken into account, as noted in Section 4.3.3. There may well be little loss of efficiency in, for example, the use of lead aprons in diagnostic and interventional radiology.

The orientation of a worker's body in relation to the location and orientation of the radiation source can result in higher dose rates for the worker than may be necessary. The worker needs to understand the origin and direction (if applicable) of the radiation. Provided that the radiation field is non-uniform, the individual needs to position himself or herself in such a way that the most exposed sensitive organs are in the areas of lowest dose rates, thus reducing doses. This is particularly applicable in the handling of medical sources and in applications of radiography.

Long handled tools and remotely operated tools are also effective in reducing a worker's dose (see the example in Section 4.3.4.1). The basic measure of increasing the distance from a radiation source can also significantly reduce doses.

4.3.4.1. Example 15: Long handled tools

Long handled tools include poles with hooks for lifting a highly radioactive filter out of a filter housing and into a shielded cask and poles with grappling devices for handling highly radioactive devices under water. Poles used in underwater applications should be perforated to allow water to pass through them, which will prevent radiation passing along the pole to the worker handling the tool.

4.3.5. Specialized training

In addition to general training, specialized training can also help to reduce exposure in the optimization process. Specialized training can be conducted in various ways. It can be conducted as a second phase of basic training that provides greater detail and hence could allow greater responsibilities for workers. Specialized training can also include such subjects as the handling and control of radiography sources or medical diagnostic sources. Specialized training will be commensurate with the workers' risks and should be given prior to the performance of any job in which exposure could be high.

Mock-up training and exercises are effective in that they allow workers to practice tasks without the associated risk. Individuals can perform a walk through or dry run that can help to find any problems. This will also help to identify any shortcomings in either the individuals' skills or the tools that may be used to perform the task. This training could thus help to reduce the time needed to perform the task as well as to prevent possible errors. The most effective mock-up training reproduces the actual conditions, such as poor lighting, heat or poor ventilation, of the work environment. Additionally, workers need to wear all the protective clothing and respiratory equipment that is necessary to perform the task.

Other forms of specialized training can include time and motion studies, which help to find any problems specific to the task to be performed. This can also include a study of the worker's body orientation to help to reduce the whole body dose.

5. DEFINING AND IMPLEMENTING AN ALARA PLAN

The next step after an assessment of the programme and identification of all the actions that could be taken to reduce exposure is to decide which means of reducing exposure will be used, and to establish an implementation plan. There are actions that will be obvious and that can be implemented in the short term. Some actions may need more long term planning, however. In either case, the implementation of the plan needs to be systematic and sustained.

The range of actions can vary from policy actions taken at a high level in a nuclear power utility for managing large works to a specific action such as installing temporary shielding for a particular task. In many cases, particularly for actions that deal directly with human factors (e.g. actions for communication, awareness, education), the decision to implement these actions is straightforward and should be an integral part of the routine daily management of the programmes for radiation protection and optimization.

Whatever the size of a facility, it is necessary to identify the individual or group responsible for the overall co-ordination of efforts of the optimization programme. This responsible individual or group should also be given the authority and necessary support to carry out the duties to implement the ALARA plan.

5.1. GLOBAL COMPONENTS

Prior to discussing the detailed plans and job specific aspects of the implementation plan, the global or common aspects of an optimization plan need to be discussed. Elements that are common to the most basic optimization programmes include work management, the education of workers of the basic principles of radiation protection and optimization, raising awareness on the part of the workforce of the optimization process and the features of an effective communication process.

Good work management includes an evaluation of the radiological conditions at the time a specific task is scheduled to be performed. Opportunities may exist where specific tasks can be performed at another time, when radiological conditions are less hazardous. The general education of workers is a primary element of the experience of radiation work on which other elements of training and experience can be built.

Awareness on the part of workers of the optimization process and of the existence of an effective communication process in an optimization programme mutually reinforce one another. Without one it is unlikely that the other could exist. Effective communication and awareness on the part of workers is accomplished through open dialogue within and between all levels of management and the workforce. Successful implementation of an ALARA plan is also dependent on the level of commitment from all personnel at the facility concerned.

Support from and involvement of senior management is imperative for several reasons. Management needs to be aware of the needs and the progress of various exposure reduction activities in order to make informed decisions. The commitment of workers to the optimization process will increase as the commitment of management increases. Furthermore, involving managers in the optimization process will raise their awareness of issues that are difficult to resolve at lower levels. Senior managers can be involved through various means, either as part of an oversight committee or singly, depending on the size of the facility concerned or as the situation warrants (see the example in Section 5.1.1).

All related work groups (those receiving occupational radiation doses) need to be involved in the optimization process. A particular work group’s level of involvement needs to be commensurate with the level of dose received by that group. Those groups that are able to influence the exposure conditions should also be involved. Task assignment and accountability concerning execution of the plan at the level of basic tasks will facilitate the management of the plan. Individuals should be given task assignments in their respective area of expertise as it pertains to optimization. Responsibility and accountability are critical in this part of the process. Routine follow-up meetings should report the status and progress of the assigned action items and responsibilities.

5.1.1. Example 16: Creation of specific ALARA management structures

In some facilities it may be useful to create specific ALARA management structures to facilitate the co-ordination and implementation of actions. These structures may include:

- *An ALARA committee.* This committee is responsible for approving and reviewing the ALARA plan. It meets periodically to review the performance of the facility concerned in relation to radiation protection, to evaluate suggestions for reducing doses and to make recommendations to higher management. Members are generally selected to provide a wide range of technical backgrounds to the committee and to ensure that the various work groups are represented.
- *An ALARA co-ordinator (or ALARA group).* This co-ordinator (or group) verifies that the decisions taken by the ALARA committee are implemented. He or she is also the designated contact person between the workforce and management for discussing radiation protection issues. When a group is created it is usually composed of engineers, health physicists and technicians, and is in charge of performing a detailed analysis of jobs suitable for ALARA.

5.2. ANALYSIS AND SELECTION OF JOB SPECIFIC OPTIONS FOR DOSE REDUCTION

5.2.1. Analysis of options

When the decisions concerning the implementation of some job specific means to reduce exposure are not straightforward, it is necessary to assess the actions more precisely in terms of the effectiveness of dose reduction, relative costs and feasibility of implementation in a given time frame (short or medium term). This evaluation needs to be done especially when several options for dose reduction are envisaged for performing one specific job in order to select the most appropriate ones, or when various combinations of dose reduction options are envisaged and will affect groups of jobs.

An evaluation of the effectiveness of the options should be looked at in terms of the net collective dose, taking into account dose savings and possible dose increases when the options give rise to trade offs in doses between workers. Depending on the exposure situations, such as the collective dose savings per job, per group of jobs, per category of workers for a given job or group of jobs, per year or for the lifetime of the facility, several estimations can be made. At the beginning of an analysis those indicators are selected that are the most relevant for the optimization study under consideration.

Depending on the conditions of exposure, it might also be necessary to analyse the evolution of the annual individual dose distributions according to the options for dose reduction. This factor is particularly important at the design stage of facilities or when the options may significantly modify the annual level of individual doses for a given category of worker (see the example in Section 3.1.1.2).

An evaluation of the options for dose reduction should include a quantification of the investment and operational costs generated by their implementation. The level of detail applied in the cost evaluation should, however, be commensurate with the global cost at stake. Cost estimates should be expressed as a net cost, in consideration not only of the cost increase engendered by the options but also of the possible savings in terms of the reduction of operational costs (see the example in Section 5.2.1.1). Specific attention needs to be paid to including the estimations of the indirect costs generated by the implementation of the options (for example waste management costs induced by decontamination).

Whatever their level of detail, the cost estimates should be expressed in the same time units as the dose savings. For example, dose savings calculated on an annual basis need to be put into perspective with annual costs. In the same way, for job related dose savings costs need to be calculated per job.

5.2.1.1. Example 17: Identification of cost savings

Cost savings can be obtained by means of reducing the duration of a task and the number of workers, reducing salary costs, reducing costs due to the interruption of the main activities of the facility concerned or reducing the purchasing and waste costs associated with the use of protective suits.

A reduction in the levels of individual doses may allow a category of workers to perform other jobs during the year without reaching the individual dose limit. In such cases it would be considered that ‘replacement’ costs are saved; that is, all the costs that would be generated by the need to train, educate and employ other workers so that they can perform the same jobs. Another aspect is the benefit of retaining experienced teams that know the jobs better than a new team that has not previously performed the jobs concerned.

5.2.2. Selection of options to be implemented

One important element in the decision making process is to identify clearly the framework in which the decision has to be taken; that is, the financial constraints (i.e. the existence of a specific budget for the reduction of doses, an overall budget for the facility), the technical or time constraints (i.e. the time available before performing a job compared with the time necessary to implement or develop another option) and, at the design stage, individual dose constraints. In some cases there may be a need to consider whether specific maximum individual dose levels have been fixed for the job. The identification of those constraints gives rise to the setting of a defined set of clear decision criteria, which favours the coherence and openness of decision making and efficiency in the allocation of resources for protection.

When the selection of an option is not obvious or too complex, when several options could be implemented or when a major investment could be necessary, decision aiding techniques can help to clarify the decision (see Annex I). When quantifiable factors are considered, cost–benefit analysis or other quantitative techniques can be used. These techniques rely on the use of a monetary value of the unit of the collective dose (the so-called 'alpha value', or 'monetary value of the man-sievert'), which represents 'how much money is it agreed to spend in order to avert one unit of the collective dose'. This reference value is a tool that, in the decision making process, helps to classify the options as a function of their cost effectiveness ratio and increases the openness and reduces the subjectivity of the decision. (See Annex III for the determination and use of the alpha value.)

In some cases it may not be possible to quantify all the factors involved or to express them in commensurate units. It may also be difficult to make the balance between collective and individual doses, or savings in dose and increases in amounts of waste, or to take account of broader social factors. For such situations it may be useful to utilize qualitative decision aiding techniques such as multicriteria analysis.

Decision makers need to keep in mind that decision aiding techniques do not necessarily provide the definitive answer, or the only possible solution, or an obligation to implement all of the cost effective options. These techniques need to be seen as tools to help in approaching problems in order to compare the relative effectiveness of the various possible options for protection, and to help identify all relevant factors and to include them in decision making. They can also help in the presentation of options to senior management.

5.3. MONITORING THE EFFECTIVENESS OF AN ALARA PLAN

In view of the need for continuity and the long term application of ALARA concepts, it is necessary to monitor the effectiveness of the implementation of an

ALARA plan in all its aspects. ALARA plans have both global, long term components and more job specific and directed aspects, so the monitoring and feedback need to cover both. The effect of some elements, such as the general level of education of the workers and the raising of awareness, are difficult to monitor in isolation. What is needed for these elements are global indicators, such as trends in individual doses, in collective doses and in the frequency and severity of accidents or incidents. By contrast, the effectiveness of those parts of the plan that deal with specific jobs can be directly checked and documented. Record keeping and documentation will ensure that data are available for subsequent reviews and refinements of the ALARA plan.

Since the objective of the optimization of radiological protection is to reduce individual and collective doses, the most relevant indicator is the dose (collective or individual). The effectiveness of an ALARA plan, in a global sense, can be graded on the basis of the level of the reduction of individual and collective doses. While a downward trend in doses is always desirable, it does not necessarily indicate that an ALARA plan is successful.

There are other factors, such as water chemistry in a nuclear power plant, that can affect doses. It is necessary, therefore, to collect and evaluate all the data to explain any trend in exposure. Success and the need for improvement can be easily and routinely monitored through the use of indicators, as described in Section 3.1.2. This monitoring should include trend analysis, so that any favourable or adverse trends can be noted and explained.

The effectiveness of an ALARA plan can be further monitored by means of feedback from individuals or groups by any formal or informal process of communication (i.e. post-job reviews, suggestions concerning ALARA). The information received by means of this process can be used to monitor the overall attitude of the workforce as well as to provide a measure of its awareness of and commitment to the optimization process (i.e. a measure of the development of an ALARA culture).

According to the size of the facility concerned and the amount of feedback received from workers, these suggestions should be documented and tracked as for the action items assigned in the plan implementation process, as discussed in Section 5.1. This will also provide an opportunity to provide information to the workforce on the status of these suggestions, which will improve awareness and enable workers to see the results of their efforts to reduce exposure.

The results of an ALARA plan should be addressed in reports generated by periodic review (perhaps a quarterly status report). Reviews should include comparisons of the exposures for repetitive jobs from one iteration to another, as well as comparisons with the results achieved at similar facilities elsewhere in the industry (benchmarking). Representatives from both management and the work groups should be involved in the review process.

This review process should further be used to evaluate and analyse performance such that corrective actions can be specified to address any adverse trends. Corrective actions should be incorporated into the implementation plan and would be a part of the developing culture of the optimization of protection. Corrective actions should be clearly presented as the responsibility of the affected groups, and the resolution of problems and the development of methods to improve performance should be an expectation of senior management. This reinforces the concept of accountability. As successful results are achieved, periodic reviews will also help to identify those means that need to be continued or any new means that may be introduced to improve the process of reducing exposures.

6. CONCLUSIONS

It is often stated that the main emphasis in radiation protection is on the optimization of protection. This phrase, however, does not readily bring to mind what actually needs to be done in the workplace to implement optimization. In this Safety Report an attempt has been made to demystify the concept by describing in direct terms what is to be done to carry out an optimization process and to free the way of thinking that is the foundation of optimization from excessive reliance on analytical techniques such as cost–benefit analysis, as these techniques are merely tools. In order to do this the acronym ALARA has been used in this Safety Report as it brings to mind the twin concepts of dose reduction and reasonableness.

In describing a general approach to optimization considerable attention has been paid to the full and systematic evaluation of the radiological conditions in a workplace. This analysis is crucial as it forms the basis for understanding what needs to be done, what can be done and what are the available approaches to getting it done. It also documents the starting conditions so that the effectiveness of the implementation of an ALARA plan can be monitored.

The other main component of this Safety Report is a general review of the means that are likely to be available in most workplaces to reduce exposure. These are divided into global means, which can be applied throughout an organization, and those that are more job specific. Some of these global means are no more than would be expected in any well managed organization, such as an application of effective and efficient procedures for the management of work and provision for the education and training of workers. A well managed and effective organization that pays due regard to the safety of its workers will recognize the benefits of these means without the application of a complex decision analysis. There are, however, situations in which the optimization of protection with respect to particular jobs is needed. In many of these cases it will still be clear that measures to reduce doses can be taken with little cost or even with savings through increased efficiency, or conversely that in other cases the necessary allocation of resources would be disproportionate to the dose reductions. Nevertheless, there will be some cases in which it will not be obvious how much it is appropriate to do to reduce doses in a cost effective manner; some form of decision aiding technique can be helpful in such cases.

The outcome of an evaluation and analysis of options for improvement results in what has been called in this Safety Report an ALARA plan. This is a combination of short term and long term or continuing actions. The effectiveness of an ALARA plan depends on commitment on the part of the management and workforce, which is fostered by the participation of both groups in the ALARA plan's formulation. Monitoring the effectiveness of an ALARA plan provides the necessary feedback for sustaining appropriate attitudes to ALARA throughout an organization in the longer term.

The approach described in this Safety Report is intended to be general and has therefore been expressed in broad terms. The examples given are intended to show how the approach can be and has been applied in different circumstances. The application will be at a different level of detail for a large facility or a small company, but in all cases the general approach set out can be adopted and applied for the benefit of radiation workers, managers and their organizations.

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Annex I

DECISION AIDING TECHNIQUES

I–1. INTRODUCTION

Although it is not the purpose of this Safety Report to discuss decision aiding techniques, this short annex gives sufficient information such that the references in the text to such techniques of different types are understandable. To apply the techniques in practice it will be necessary to consult the references for more detail.

An essential component of the ICRP's approach to optimization has been to quantify the optimization studies, wherever this can be done. In earlier publications [I–1, I–2] the technique recommended is cost–benefit analysis. In Ref. [I–3] cost–benefit analysis is given as an example of a technique, but other techniques are also developed and recommended for use. Practical guidance on the application of these techniques has been given [I–4, I–5]. The result of the application of any quantitative decision aiding technique is called the analytical solution. In reaching a recommendation for an optimum, however, this has to be combined with a qualitative assessment of the performance with respect to the other radiological protection factors. The result of this combination is then fed into the final decision making process.

Of the different techniques available, four are described in Ref. [I–3]; these are cost effectiveness analysis, cost–benefit analysis, multiattribute utility analysis and multicriteria outranking analysis. An essential point that is not always recognized is that it is the specification of the radiological protection factors and the criteria to be used in the analysis that determines the outcome, not the technique chosen. If it is decided that only two factors are relevant, for example the cost and collective dose, then a simple technique such as cost–benefit analysis will give an analytical solution that directly indicates the optimum. The application of a more complex technique to such a simple problem is superfluous, but if it were done then the same analytical solution and optimum choice would result. If, however, it is decided that a number of factors are relevant, and especially if some are difficult to quantify, then a simple technique will only deal with some of the factors and the analytical solution does not indicate the optimum; it has to be combined with a qualitative assessment of the options with respect to the remaining factors before the optimum can be found. This combination of quantitative and qualitative inputs to the decision on an optimum is something that has not always been clearly recognized.

Although cost effectiveness analysis has been used, it only enables the selection of an option that either minimizes the collective dose for a fixed protection cost or minimizes the protection cost for a specified collective dose saving. However, neither of these cost effectiveness procedures corresponds to the optimization of protection, since they do not involve the fundamental trade off between the cost of protection and the dose.

I–2. COST–BENEFIT ANALYSIS

The next stage up from cost effectiveness analysis is cost–benefit analysis. This is an old technique and was the first technique to be introduced by the ICRP in the context of optimization. The focus of the technique is on aggregated monetary measures of costs and benefits associated with options, the objective being to identify the option having the minimum total cost. This can be carried out either by a total cost analysis or by a differential analysis. These are only different mathematical techniques.

In the early publications of the ICRP a simple formulation of cost–benefit analysis was derived. In this, the only factors deemed to be directly relevant for optimization were the financial costs of implementing protective measures and the associated levels of collective dose. In these circumstances a simple cost–benefit analysis can be carried out by transforming the collective dose into a monetary value using a reference value of unit collective dose, generally denoted as the alpha value. The derivation of this value is described in Annex III.

The analysis then proceeds by adding the cost of protection X and the derived cost of the detriment Y (= αS) in order to obtain a total cost $X + Y$. The externally specified criterion needed to obtain the figures is the value of unit collective dose, α. The total cost for each option represents a figure of merit and the analytical solution corresponds to the option that minimizes the total cost.

However, this analytical solution only deals with two factors, namely the cost and collective dose, so that, in moving from this analytical solution to a recommended optimum option any other factors have to be considered in a qualitative fashion.

I–3. EXTENDED COST–BENEFIT ANALYSIS

The cost–benefit analysis technique considered above is strictly limited to quantitative comparisons between protection costs and the collective dose. However, the cost–benefit analysis framework can in principle be extended. One possible extension is to cover the individual dose distribution. One of the radiological protection factors regarded as relevant is whether the individual doses are high or low. This can be expressed as a difference between a collective dose arising from a large number of low individual doses and the same collective dose delivered to a smaller population receiving higher doses. One method of incorporating this judgement is to modify the value assigned to the unit collective dose by adding an extra term to the cost of detriment. This new component of detriment cost has been expressed by the ICRP in Refs [I–2, I–3] as a beta term. The detriment Y is then defined as:

$$Y = \alpha S + \beta_j S_j$$

where

β_j is the additional value assigned to the unit collective dose,
S_j is a function of the level of the individual dose among the group of workers concerned.

By applying this formula it is possible to assess the cost of detriment as the sum of the alpha term, the collective dose and the beta terms, and the individual dose distribution being taken into account. The inclusion of an allowance for the individual dose distribution leads to an increase in the cost of the detriment Y and modifies the total cost for each option. However, other relevant factors may still be omitted from the quantitative analysis and need to be included in a qualitative fashion.

I–4. MULTIATTRIBUTE UTILITY ANALYSIS

Cost–benefit analysis is powerful but it is also possible to utilize a different kind of technique, different not in its fundamentals but in the way that it deals with the factors involved. This technique is known as multiattribute utility analysis. The essence of the technique is to use a scoring scheme called a utility function for the relevant factors, with the property that if the score or the utility is the same for two options then there is no preference for one or the other. An option is preferred if it scores higher than the other.

In Ref. [I–4] an everyday example was used to introduce the idea of multiattribute utility analysis and how quantifiable and non-quantifiable factors are used together with judgemental processes in reaching a decision. In buying a car we assess such factors as the price, the cost of maintenance and the efficiency in terms of fuel consumption. These could be included quite easily if we were to carry out a cost–benefit analysis, possibly within an overall constraint such as how much money we have available. However, in assessing other factors, such as the desired acceleration or top speed, the colour of the paint or the quality of the sound system, cost–benefit analysis is not so easy to apply. Nonetheless, we recognize all of these as factors in the decision, we score each option — each potential car — according to our own attitude towards the factor, and then we trade off between the factors using our own personal criteria. The studies made by each of us would use the same database — the characteristics of the different cars — but the decisions we reach may differ because of our individual attitudes to the factors and our own criteria for trading off one factor against another. For example, one person might attach more weight to fuel economy and acceleration, whereas another might attach more weight to the choice of colour or to the quality of the sound system. The final decision will, of course, depend upon the judgement of the decision maker.

In applying multiattribute utility analysis it is necessary to specify the radiological protection factors and to quantify the consequences of each protection option in terms of these factors; in other words, to carry out the same initial procedure as for a cost–benefit analysis. It is then necessary to generate for each factor a utility function that gives the relative desirability of the possible outcomes for this factor. Generally the best outcome or the lowest adverse consequence for each factor is assigned a utility of 1 and the worst consequence a utility of 0.

A major advantage of this technique is that these utility functions need not necessarily be linear. This enables variations in attitude with the magnitude of consequence to be introduced into the quantitative decision making process. It is also possible to use the technique of multiattribute utility analysis to include the factors not normally regarded as quantifiable by assigning utility functions to the various values of the factor. For example, if some options necessitate protective clothing, those will have an impact on the ease of carrying out tasks. The maxi-mum utility value of 1 is clearly assigned to the option not involving protective clothing, and the minimum utility value of 0 to the option in which it is difficult to work.

I–5. MULTICRITERIA OUTRANKING ANALYSIS

All of the techniques considered so far are aggregative techniques, in that they combine all of the attributes that represent the relevant factors that influence a decision into a single figure of merit, whether this is a total cost, as in cost–benefit analysis, or a total utility function, as in multiattribute utility analysis. However, in order to carry out this aggregation there are two conditions to be satisfied. Firstly, it is necessary for all the factors to be commensurable, so that the total value that is finally assigned adequately expresses the contribution to the consequences for each of the factors involved. Secondly, the decision maker needs to accept that a poor performance on one factor can be compensated for by better performances on other factors, and that such trade offs are acceptable over the full range of consequences that arise from all the options for protection that are being considered.

These two conditions may give some difficulties if the factors being considered are heterogeneous or if they can be evaluated only in a qualitative manner. Alternatively, where some consequences of options for protection are rather extreme, it may be judged that the trade off is not acceptable over the full range of consequences. In these circumstances a technique that deals differently with the range of consequences could be more useful. Such a technique will not be described further here, but is included in Ref. [I–3] as an example of a different approach to the optimization of radiological protection.

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Annex II

ALARA CHECKLISTS

Checklists are useful tools for meeting the needs of an optimization programme; their uses are varied. Among their uses are that they can be used as agendas for job planning or post-job review meetings and that they can be distributed to workers to provoke thought for a process of information feedback. There are a variety of checklists; it is likely that they will vary depending on the type and size of the facility concerned. Included in this annex are specific examples from a typical nuclear power plant in the United States of America and some checklists developed by the Centre d'étude sur l'évaluation de la protection dans le domaine nucléaire (CEPN), France.

TABLE II–I. US REACTOR CHECKLIST 1: ALARA JOB PLANNING CHECKLIST. RADIOACTIVE WORK ORDER REVIEW

Pre-job review questions	Yes	No	NA[a]	Comments
1. Has the job history been reviewed? (a) If no, have plans been made to start or improve files during this job? (b) Will the use of photographs or videotapes be helpful? If yes, indicate by name who will take photographs and/or videotapes.				
2. Have job interferences been identified (i.e. anything that may hold up work progress unnecessarily)?				
3. Is the job a high risk or first time evolution?				
4. Will special training or mock-up training be required? If yes, indicate schedule, location and type.				
5. Will remote handling devices or monitoring be utilized? If yes, specify.				
6. Does all the work need to be performed in a radiation area or airborne area? Specifically, can the component(s) be moved to a lower dose area? Has prefabrication outside the radiation area been considered for the new components being installed?				
7. Can area dose rates be reduced through the use of shielding or system flushing (to remove the source)?				
8. Have alternate work methods been identified for exposure reduction potential? If yes, what alternate methods were identified?				
9. Will the job necessitate a radioactive system breach?				
10. Has a tool list been developed and verified to be accurate?				
11. Will special tools be needed? If yes, what type and are they staged?				
12. Will the job generate radioactive waste? If yes, what type (e.g. liquid, dry active waste, metal) and approximate volume?				
13. Have job site communication requirements been determined? If yes, describe.				

TABLE II–I. (cont.)

Pre-job review questions	Yes	No	NA[a]	Comments
14. Has the work area been reviewed for environmental conditions and restrictions? Describe any limiting conditions or restrictions.				
15. Has the word order and procedure been reviewed to identify radiation protection hold points (i.e. work steps that could result in the radiological conditions changing)?				
16. Has a list of available, qualified members of the work crew been reviewed to ensure distribution of the crew's doses?				

[a] NA: not applicable.

TABLE II–II. US REACTOR CHECKLIST 2: RADIATION PROTECTION REVIEW

Pre-job review questions	Yes	No	NA[a]	Comments
1. Is a job planning meeting needed?				
2. Is a pre-job brief required?				
3. Is an exposure budget and an exposure goal established for the job?				
4. Will component or area decontamination be performed?				
5. Will temporary shielding be effective in reducing the collective dose for the job? If yes, indicate temporary shielding ratio in 'comments'.				
6. Are engineering controls for airborne radioactive material planned?				
7. Have low dose waiting areas been identified?				
8. Has the use of respiratory protective equipment been evaluated to determine its affect on the exposure estimate if used?				

[a] NA: not applicable.

TABLE II–III. US REACTOR CHECKLIST 3: ALARA PRE-JOB BRIEFING CHECKLIST

1. Describe a brief sequence of events.
2. Describe the work area from the list of concerns below:
   - (a) Radiological conditions at the start of the job;
   - (b) Potential radiological conditions and/or hazards as work progresses;
   - (c) Access routes to and from the work area;
   - (d) Identify low dose waiting areas for the staging of equipment and/or support personnel;
   - (e) Environmental conditions and restrictions;
   - (f) Shielding concerns;
   - (g) Safety hazards (e.g. heat stress, confined space entry).
3. Describe the equipment and/or methods to be used to control the generation or spread of contamination and to minimize the potential for airborne radioactive material.
4. Describe the housekeeping and system cleanness that precludes foreign materials from entering open systems.
5. Describe the requirements, placement and use for dosimetry.
6. Describe requirements for protective clothing, equipment and respiratory protection.
7. Describe the dress and/or undress methods particular to this job.
8. Describe the techniques of volume reduction for radioactive waste and considerations for special waste (e.g. oils, packing, filter, mixed waste) handling and generation.
9. Have all the action items identified on the ALARA job planning checklist been completed? If no, what items remain and who has responsibility for their resolution?
10. Open the discussion to solicit comments and concerns of the work crew.

TABLE II–IV. US REACTOR CHECKLIST 4: ALARA POST-JOB DEBRIEFING CHECKLIST

Post-job review questions	Yes	No	NA[a]
1. Was a formal pre-job briefing conducted and documented?			
2. Were necessary services ready and available when needed?			
3. Did the specified tools meet the needs of the job?			
4. Did the work progress as planned? If no, indicate why not.			
5. Were job site communications satisfactory?			
6. Was the work order and/or procedure adequate to perform the work?			
7. Were the environmental conditions conducive to smooth progress of the work?			
8. Was the amount of radioactive waste generated minimized?			
9. Were controls adequate to contain contamination to the work area?			
10. If respiratory protection was used, were efforts made to eliminate airborne radioactive material and preclude the use of respirators?			
11. Did radiological conditions reflect pre-job surveys?			
12. Open the discussion for comments and offer the personnel statement sheet. (Check all that apply.)			
Was the scope of the job changed or extended?			
Were difficulties encountered in scheduling and/or work co-ordination?			
Was there a failure of tools and/or equipment?			
Were there wrong or unavailable parts and/or tools and/or equipment?			
Were there unplanned requirements for the preparation of the job site?			
Was there interruption and/or interference by other work activities?			
Were there inadequacies in work orders and/or procedures?			
Are the radiological conditions at the job site changed?			
Was there inadequate compliance with radiological controls?			
Was there inadequate consideration of good ALARA practices?			
Was there inadequate shielding?			

[a] NA: not applicable.

TABLE II–V. CEPN CHECKLIST 1: PRE-JOB REVIEW CHECKLIST

	Yes	No	To be studied
Is there previous experience of similar operations?			
Has it been taken into account?			
I. Actions on sources			
Before shutdown: chemical filtration?			
Decontamination?			
Is it possible to maintain water in circuits?			
Removal of a highly radioactive material?			
Other?			
II. Protection			
Biological shielding: is it fixed, mobile, integrated with the machinery?			
Against contamination: is a glovebox available?			
Shielding?			
Is shielding integrated with the tools?			
Static containment?			
Dynamic containment?			
Sprinkling and drainage?			
Adapted individual protection?			
III. Volume of work under conditions of exposure			
Is this an essential task?			
Is the procedure optimal?			
Is the task correctly scheduled?			
Is the task to be executed entirely in an irradiated zone?			
May some operators be moved to a distance?			
Is the number of operators justified?			
Is the distribution of work optimized?			
Can doses be spread between operators?			
Are there special tools for reducing doses?			
Is there an opportunity for remote control or robotics?			
Can clothing be modified to facilitate the work?			
Is there an opportunity for improvement to ambient conditions (e.g. temperature, lighting)?			
Is there an opportunity for radio communications?			
Is there an opportunity for televisual surveillance?			
Is there an opportunity for easier access?			
Is handling equipment available?			
Are there adequate superstructures (e.g. scaffolding)?			
Are there standing and procurement areas?			
Are there procedures for packing equipment and packaging waste?			
Are there procedures for the removal of material?			

TABLE II–VI. CEPN CHECKLIST 2: FEEDBACK EXPERIENCE MEETING GUIDE SHEET

Task:

Meeting participants:

All the questions must be answered as fully as possible so that the task might be assessed and used as the basis for modifications during future work.

1. Were the tools and equipment required for the operation available at the right time?
2. Was the zone prepared and ready for your task on your arrival?
3. Were the protection measures suitable for the task executed in this zone?
4. How much time did you have to prepare the task? Was this long enough?
5. Did other tasks interfere with yours?
6. Was the work location kept clean and orderly so as to ease your work?
7. Was the full team aware of its exposure? Did you insist on this exposure being limited as much as possible?
8. Was the entire team aware of the site dose targets? Was the team motivated?
9. Were there any problems of co-ordination with other specialities, other departments or other workers?
10. What problems did you encounter that could have resulted in higher doses?

TABLE II–VII. CEPN CHECKLIST 3: CHECKLIST OF ACTIONS NOT TO BE OMITTED — AUDIENCE: UTILITY AND CONTRACTOR MAINTENANCE WORKERS

	Yes	No	NA[a]
Planning			
Do you know exactly what you have to do?			
Do you know the route to your work?			
Have you checked that your work will not interfere with that of others?			
Have you checked your tools before entering the zone?			
Have you checked that no tools are missing and that all are in a proper operating condition? Are the tools suitable for the environment?			
Environment			
Are you aware of the exposure conditions of the work?			
Dose rate?			
Risks of contamination?			
Positions of the main sources?			
Doses expected?			
Do you know what collective shielding is planned and how it is to be positioned?			
Do you know what respiratory protection equipment you must use?			
Do you know where you are to work?			
Do you know where the electrical outlets and utility connections are?			
Do you know what the nearest fallback point is for studying your work procedure sheet or waiting for another job to be completed?			

If you do not know the answers to any of these questions, ask your team leader or the plant's radiological protection worker.

[a] NA: not applicable.

TABLE II–VIII. CEPN CHECKLIST 4: CHECKLIST OF ACTIONS NOT TO BE OMITTED BEFORE OPENING A JOB SITE — AUDIENCE: TEAM LEADERS

Hold a briefing session with the team before entering the controlled zone.

In the briefing session, describe the work to be carried out.

In the briefing session, describe the place where the work is to be carried out and the best route there in view of the radiological conditions (such as the locations of hot spots).

If necessary, describe any environmental constraints liable to complicate the use of tools and execution of the work (e.g. space, lighting, scaffolding, biological shielding in place).

Indicate:

The provisional map
The risk of contamination
The protection provided and its location
The doses anticipated in performing the work

Indicate the fallback points.

Indicate how the work is scheduled relative to previous and subsequent work at the same place.

If you lack any of this information, ask the job co-ordinator and/or the radiological protection worker.

Annex III

MONETARY VALUE OF THE UNIT COLLECTIVE DOSE

III–1. INTRODUCTION

The optimization of radiation protection is aimed at finding an efficient allocation of resources for protection in order to reduce doses ALARA, social and economical factors being taken into account. An economic tool, represented by the monetary value of the unit collective dose and the use of cost–benefit analysis, has been developed to help decision making in the context of a limited availability of resources for protection purposes and a decreasing efficiency of investment in protection. The main objective of using this tool is to allow a greater openness of decisions by introducing a certain rationality into the selection of investments.

The attribution of a monetary value to dose savings by various options for radiation protection is a means of defining how much money it is agreed to spend in order to avert one unit of the collective dose, that is some potential radiation induced health effects, given the resources available for protection purposes and the characteristics of the exposure situations.

In using cost–benefit analysis three main data need to be distinguished:

— The monetary value of the man-sievert, which is an a priori defined reference value.
— The protection cost associated with a specific option, which is the amount of money that will be spent if the option is implemented.
— The implicit cost of the averted man-sievert associated with a specific option, which is the ratio between dose savings and the cost of protection associated with the option. This represents the cost of averting one man-sievert if the option is implemented.

When the implicit cost of the averted man-sievert associated with an option is well below the reference monetary value of the man-sievert, the option can be seen as being reasonable in terms of cost effectiveness. If the implicit cost is greater than the reference monetary value of the man-sievert, then, on the basis of the criterion of cost effectiveness only, the option is not judged to be reasonable (since it costs more than the amount that it has been agreed to spend to avert one unit of the collective dose). In all cases, in the final decision on implementing the option other factors and criteria will need to be taken into consideration.

It is necessary that the economic tool be used as a decision aiding tool that allows the selection of protection options to be facilitated and structured in a context of complex decision making. It should not be used alone in the decision making process, but as part of a predefined set of decision criteria (e.g. technical, political).

III–2. EVALUATION OF THE REFERENCE MONETARY VALUE OF A MAN-SIEVERT

As mentioned above, the monetary value of a man-sievert is an a priori value that indicates how much one is willing to pay in order to avert a collective dose of one man-sievert. This value can be defined by various organizations. In most cases it is defined directly by the facilities concerned as part of their decision making rules. However, in some cases the national authorities for safety or radiation protection make recommendations on the basic value to be used in the optimization process. In all cases, though, the monetary value of a man-sievert is set by reference to the potential health effects associated with the doses and resources available for the purposes of protection in the facility or country concerned. If necessary, evaluation can also include consideration of the level of individual doses or individual dose distributions.

III–2.1. Dose–effect relationship and the monetary value of health effects

The main step in the determination of the monetary value of a man-sievert relies on the consideration of the dose–effect relationship. It is thus the existence of a potential health risk associated with any level of dose that justifies the willingness to reduce doses ALARA. By adopting, as recommended by the ICRP [III–1], the assumption of a non-threshold linear dose–effect relationship, the monetary value of a man-sievert can be evaluated by multiplying the probability of developing a health effect associated with a collective dose of one man-sievert by the monetary value of the health effect. As health effects (cancers and hereditary effects) can be expressed as a loss of life expectancy, their monetary value can be related to the monetary value associated with one year of life. Two main methods can be used for the valuation of the loss of life expectancy:

- The human capital approach, whereby the monetary value of one year of life lost is given by an economic aggregate, usually the annual gross domestic product per inhabitant (see the example in Section III–2.1.1);
- The willingness to pay approach, which uses contingent valuation surveys to reveal an individuals’ preferences when a specific risk has to be reduced.

III–2.1.1. Example III–1: Calculation of the monetary value of a man-sievert using the human capital approach

— Average loss of life expectancy associated with a radiation induced health effect (fatal cancers and hereditary effects): 16 years.
— Gross domestic product per caput per year: US $22 400.
— Monetary value of a radiation induced health effect: US $22 400 × 16 = US $358 400.
— Probability of the occurrence of a radiation induced health effect for workers: 5.6×10^{-2} Sv^{-1}
— Monetary value of a man-sievert: US $358 400 × 5.6×10^{-2} ≈ US $20 000/man·Sv.

III–2.2. How to take account of individual dose distributions

In Ref. [III–1] the ICRP emphasizes the need to take into consideration the possible inequity in the individual dose distributions that could result from the implementation of protection options. It follows that the objectives of the optimization of radiation protection are to obtain a reduction of the individual and collective doses, with priority given to the highest individual doses.

Applying these objectives to the monetary value of a man-sievert means that one would accept paying more in order to avoid a unit of the collective dose when the individual dose increases, and, moreover, that this increment of the monetary value of a unit of the collective dose becomes increasingly important. Some models that allow the determination of such an increasing value of a man-sievert have been developed (see the example in Section III–2.2.1); these lead to a system of monetary values of a man-sievert that depend upon the range of individual doses [III–2, III–3].

III–2.2.1. Example III–2: A model to determine a set of monetary values of a man-sievert according to the level of individual doses

This model assumes that under a certain level of individual dose it is more appropriate to assume a constant monetary value for the unit of the collective dose [III–3]. Above this level the monetary value of a man-sievert increases with the level of the individual dose, with account taken of the degree of aversion to the level of dose.

This model is illustrated in Fig. III–1, where the ordinate is the monetary value of the unit of the collective dose and the abscissa is the individual level of dose, generally in terms of mean annual dose.

Proposed values for the model. In practice, in order to implement this model it is necessary to give a value to three parameters: α_{Base}, d_0 and a:

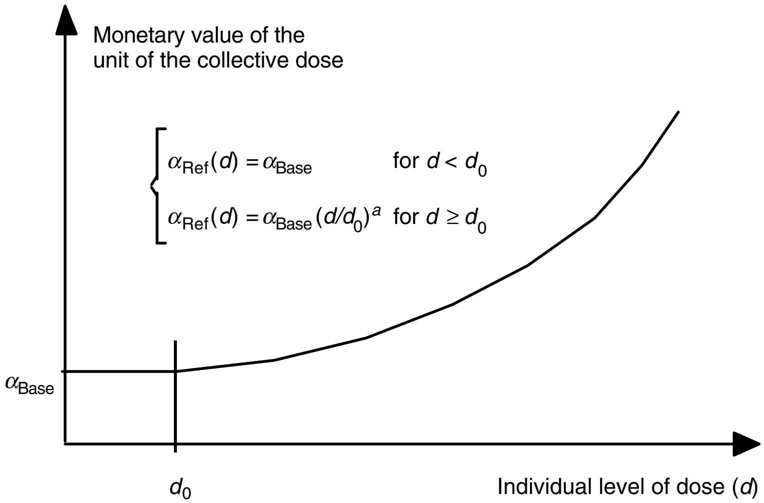

FIG. III–1. A proposed model for the monetary valuation of the radiological detriment.

- α_{Base} represents the monetary value of the health detriment associated with one unit of the collective dose.
- The value of d_0 corresponds to the level of the individual dose below which the aversion to the level of dose is not considered. This value depends upon the degree of acceptance of risk for the exposed population. In the case of occupational doses, for example, the value corresponding to the limit of the individual dose for the public (1 mSv/a) was adopted (this value could be adapted according to the specific situation considered).
- The *a* coefficient reflects the degree of aversion to the level of the individual dose. It has been demonstrated that *a* must be greater than 1 to satisfy the objectives. In the case of occupational doses a range of values between 1.2 and 1.8 seems reasonable on the basis of a review of the literature on risk aversion.

III–3. EXAMPLES OF MONETARY VALUES USED FOR THE UNIT COLLECTIVE DOSE

A survey of practices at the international level shows that the concept of assigning a monetary value to a man-sievert is increasingly widespread among operators and regulatory authorities, although its use is only recommended, not compulsory [III–4] (see Tables III–1 to III–3). The monetary value is primarily used to inform important decisions (e.g. on the modification of installations or costly repairs). It is primarily seen by users as a tool that reduces the subjectivity of choice and that is occasionally used in discussions with subcontractors or authorities.

TABLE III–1. MONETARY VALUE OF A MAN-SIEVERT RECOMMENDED BY DIFFERENT AUTHORITIES

Country (year)	Monetary value of a man-sievert in the national currency	Monetary value of a man-sievert in US $
Canada (1997)	Can $100 000, established on the basis of international references	75 000
Czech Republic (1997)	CZK 500 000–5 000 000, depending on the level of the individual doses and the exposure situation	17 000–170 000
Finland (1991)	US $100 000, value common to all the Nordic countries	100 000
United Kingdom (1993)	£10 000–100 000, depending on the exposure situation (not plant specific) and the level of the individual doses	17 000–170 000
Netherlands (1995)	NLG 1 000 000	500 000
Romania (2000)	US $220 000	220 000
Sweden (SSI) (1992)	SEK 400 000–2 000 000	55 000–270 000
Switzerland (1994)	CHF 3 000 000	3 000 000
USA (NRC) (1995)	US $200 000	200 000

Note: 1 US $ = Can $1.33, CZK 30, £0.6, NLG 2, SEK 7.5, CHF 1 (as at 1998).
SSI: Swedish Radiation Protection Authority. **NRC:** Nuclear Regulatory Commission.

TABLE III–2. MONETARY VALUE OF A MAN-SIEVERT USED BY DIFFERENT UTILITIES (SINGLE VALUE)

Country	Utility	Year of adoption	Monetary value of a man-sievert in the national currency	Monetary value of a man-sievert in US $
Canada	Gentilly	—	Can $1 000 000	750 000
Romania	Cernavoda	2000	US $220 000	220 000
Slovenia	Krško	1996	US $700 000	700 000
South Africa	Koeberg	1993	US $1 000 000	1 000 000
Spain	Asco Vandellos	1994 1982	US $2 000 000 ESP 100 000 000	2 000 000 700 000
Sweden	Value common to all the utilities	1992	SEK 4 000 000	550 000
USA	Value per utility for 90% of the reactors	1990–1991 in general, 1993–1997 for the highest values	Min. value: US $500 000, max. value: US $2 810 000, medium value: US $1 200 000 average value: US $1 000 000	Min. value: 500 000, max. value: 2 810 000, median value: 1 200 000 average value: 1 000 000

Note: 1 US $ = Can $1.33, ESP 150, SEK 7.5 (as at 1998).

TABLE III–III. MONETARY VALUE OF A MAN-SIEVERT USED BY DIFFERENT UTILITIES (SYSTEM OF VALUES DEPENDING ON THE LEVEL OF THE ANNUAL INDIVIDUAL DOSE)

Country	Utility	Year of adoption	Monetary value of a man-sievert in the national currency	Monetary value of a man-sievert in US $
Belgium	SCK·CEN	1995	<1 mSv: B.Fr. 1 000 000 1–2 mSv: B.Fr. 2 500 000 2–5 mSv: B.Fr. 10 000 000 5–10 mSv: B.Fr. 25 000 000 10–20 mSv: B.Fr. 50 000 000 20–50 mSv: B.Fr. 200 000 000	<1 mSv: 27 000 1–2 mSv: 67 000 2–5 mSv: 267 000 5–10 mSv: 667 000 10–20 mSv: 1 333 000 20–50 mSv: 5 333 000
Canada	Darlington: system dependent on the category of workers	—	From a few thousand Can $ to Can $2 000 000 Example: workers in general: Can $200 000, reactor maintenance teams: Can $1 500 000	From a few thousand US $ to 1 500 000 Example: workers in general: 150 000, reactor maintenance team: 1 130 000
France	Electricité de France	1993	0–1 mSv: F.Fr. 100 000 1–5 mSv: F.Fr. 500 000 5–15 mSv: F.Fr. 2 300 000 15–30 mSv: F.Fr. 6 700 000 30–50 mSv: F.Fr. 15 000 000	0–1 mSv: 17 000 1–5 mSv: 83 000 5–15 mSv: 383 000 15–30 mSv: 1 117 000 30–50 mSv: 2 500 000
Germany	Proposal of the VGB under trial by the utilities	1996	<1 mSv: no value 1–10 mSv: DM 300 000 10–20 mSv: value growing linearly to reach DM 3 000 000 at 20 mSv	<1 mSv: no value 1–10 mSv: 170 000 10–20 mSv: value growing linearly to reach 1 695 000 at 20 mSv
Netherlands	Borselle	1992	<15 mSv: NLG 1 000 000 >15 mSv: NLG 2 000 000	<15 mSv: 500 000 >15 mSv: 1 000 000
Spain	Cofrentes: system of values dependent on the annual collective dose level	1994	<3 man·Sv per reactor per year on average over 3 years: ESP 100 000 000 >3 man·Sv per reactor per year on average over 3 years: ESP 150 000 000	<3 man·Sv per reactor per year on average over 3 years: 667 000 >3 man·Sv per reactor per year on average over 3 years: 1 000 000
UK	Sizewell	—	NRPB set for workers: between £10 000 and £50 000	NRPB set for workers: between 17 000 and 85 000
USA	South Texas	1993	<10 mSv: US $500 000 >10 mSv: US $2 500 000	<10 mSv: 500 000 >10 mSv: 2 500 000

Note: 1 US $ = B.Fr. 37.5, Can $1.33, F.Fr. 6, DM 1.77, NLG 2, ESP 150, £0.6 (as at 1998). **SCK·CEN:** Studiecentrum voor Kernenergie Centre d'étude de l'Energie Nucléaire. **VGB:** Technische Vereinigung der Grosskraftwerkbetreiber. **NRPB:** National Radiological Protection Board.

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