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DISCUSSION OF AND GUIDANCE ON THE OPTIMIZATION OF RADIATION PROTECTION IN THE TRANSPORT OF RADIOACTIVE MATERIAL

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FOREWORD

The 1985 Edition of the Regulations for the Safe Transport of Radioactive Materials, Safety Series No. 6, embodies the following requirement:

> "201. The radiation exposure of transport workers and the general public is subject to the requirements specified in the "Basic Safety Standards for Radiation Protection: 1982 Edition", Safety Series No. 9, IAEA, Vienna (1982), jointly sponsored by the IAEA, ILO, NEA(OECD), WHO."

Thus, the system of dose limitation set forth in Safety Series No. 9 is required for the transport of radioactive materials. One component of this system of dose limitation is the **optimization of protection for sources of exposure.**

In the Foreword to Safety Series No. 6 (1985 Edition) it was noted that:

> "The requirement of the optimization component of the system of dose limitation establishes that planning, designing, using or operating of sources and practices shall be performed in such a manner that exposures are as low as reasonably achievable, economic and social factors being taken into account. The Basic Safety Standards include differential cost-benefit techniques as a practical form of guidance for performing optimization of radiation protection. They also suggest that, in any further reduction in exposures economic and social factors should be taken into account so as to ensure the best use of available resources in bringing about that reduction. With regard to protection in the transport of radioactive materials, consideration must be given to optmization of (1) requirements related to package design and test requirements including quantity and external radiation level limitations and (2) operational requirements for the implementation of, and compliance with, the Agency's Regulations."
>
> "The responsibility for the development and optimization of operational requirements for the implementation and compliance with the Agency's Regulations rests with Competent Authorities in Member States and with the international organizations concerned. Recognizing the need for further guidance in this area, the Agency plans to develop, in

consultation with Member States, a Safety Series 'Guide for Optimization of Radiation Protection in the Transport of Radioactive Materials'."

This Technical Document (TECDOC) represents the first step toward providing the above mentioned Safety Series Guide. Two consultants, Mr. K. Shaw of the UK and Mr. A. Kasai of Japan, prepared a draft of this TECDOC in December 1984. Following a review period, the Agency convened a technical committee (TC-555) in June 1985 to review comments and prepare a new draft, which was then reviewed during the latter part of 1985. The resulting text is now issued as an Agency Technical Document to aid in the development of application of the optimization principles in the safe transport of radioactive materials and to encourage further developments in this field.

Following an appropriate period of application of this technical document, the Agency plans to update its contents and issue a Safety Series Guide to support the implementation of Safety Series No. 6. Therefore, comments from interested parties are welcome, and in particular comments on and further input to Appendix V are solicited, and these should be addressed to:

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A-1400 Vienna, Austria

EDITORIAL NOTE

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1. INTRODUCTION

1.1 General

The 1985 Edition of Safety Series No. 6, the Agency's Regulations for the Safe Transport of Radioactive Material[1] implements (see Foreword and paragraphs 201 and 202) the 1982 Edition of the Basic Safety Standards for Radiation Protection.[2] The Basic Safety Standards were jointly produced by IAEA, ILO, NEA/OECD and WHO and are published as IAEA Safety Series No. 9.

To meet the objectives of radiation protection, the Basic Safety Standards use the system of dose limitation recommended by the ICRP[3]. This system has three components known briefly as Justification, Optimization and Individual Dose Limitation. These components have been detailed as follows[2]:

> Justification. No practice resulting in human exposure to radiation should be authorized unless its introduction produces a positive net benefit, taking into account also the resulting radiation detriment.
>
> Optimization. All exposures should be kept as low as reasonably achievable, economic and social factors being taken into account. This requirement implies that the detriment from a practice should be reduced by protective measures to a value such that further reductions become less important than the additional efforts required.
>
> Individual dose limitation. The dose equivalent to individuals from all practices (except for medical and natural radiation exposures) should not exceed the applicable dose limits. Applying this requirement, it must be recognized that many present-day practices give rise to dose equivalents that will be received in the future. This should be taken into account to ensure that present or future practices would not be liable to result in a combined undue exposure of any individual.

This document provides guidance on the second component of the system of dose limitation as it applies to the transport of radioactive material, namely the optimization of radiation protection. It is recognized that the techniques used for optimizing radiation protection are continually developing and that the guidance provided herein on these techniques can be expected to evolve with time. Furthermore the Agency has a continuing programme for developing documents on the application of the Basic Safety Standards to the design of radiation protection systems.[4] Since transport of radioactive materials is crucial to all applications it is important that optimization is applied and that practical guidance is available in a timely fashion. This TECDOC is a first step in providing that guidance.

Generally optimization can be applied to:

- routine, normal and accident conditions of transport as set forth in Safety Series No. 6; and
- the elements of transport relating to radiation protection which include design, fabrication and maintenance of packagings, and the preparation, consigning, handling, carriage, storage in transit and receipt of packages (i.e., the packagings and their radioactive material contents).

Optimization applies to all situations where radiation exposures from a source can be controlled by protective measures and the same requirement can conceptually be used for planning emergency actions where a source may get out of control. In such situations the optimization process should take into account both the consequences and the probability of the event.

A wide range of techniques is available to optimize radiation protection, including, but not confined to, the procedures based on cost-benefit analysis. The ICRP has produced a report on cost benefit analysis, published as ICRP publication No. 37[5]. It is important to recognize that other techniques may also be used.

1.2 Scope

This document provides guidance for the optimization of radiation protection in the transport of radioactive materials. Optimization is an important consideration in the selection and design of radiation protection systems associated with transport and in the performance of transport operations. It is however important to remember that case-by-case optimization of widely used equipment may not be appropriate because it could nullify the advantages of standardization and could cause a net social loss.[3] Optimization does play a part in setting such standards and specifications and in their subsequent application.

The purpose of this document is to provide discussion and advice on the application of optimization in transport operations. The document does not provide a methodology for assessing the adequacy of the current regulatory design and testing standards. It does not set out to provide a rigid set of regulations governing optimization nor to subject regulatory evaluations too rigorously to a striving for optimum safety by Member States. It seeks instead to clearly present, as far as possible at this time, the tools and procedures for optimization in order to make it possible for all those who endeavour to do so to put optimization into practice within their own sphere of decision making. The recommendations and practical examples are intended to help producers, operators and carriers to fulfill the appropriate requirements in Safety Series No. 6 and to comply with the relevant sections of the Basic Safety Standards.

In keeping with the philosophy of Safety Series No. 6, this document describes particular actions without assigning specific responsibilities for the performance of these actions. It remains the prerogative of the organization requiring the optimization to assign specific responsibilities.

The document will focus on the following parts of the transport system: design, maintenance, preparation for transport, transport, storage-in-transit and handling. However it must be clear that some of the problems on which an optimization procedure is carried out can cause the analysis to be extended into other activities, such as quality control, preparation of materials, or any activity that can be affected by a given protection decision in transport. It is however in the handling and movement situations that transport is unique. These areas are particularly important since members of the general public may be closely involved and control has to be exercised largely by well defined technical and administrative requirements.

The need for consistent national and international controls in transport is most important and the use of agreed standards does much to facilitate transport and maintain a high degree of safety. Optimization has a role to play in the development of such standards and in their application.

The document describes a methodology for the optimization of radiation protection in transport. It provides guidance on its use in the various stages of transport and it considers occupational and public exposures. The application is intended mainly for those transport situations within the regulatory requirements where potential radiation exposures could be beneficially reduced. For example, with regard to packaging, this would be the case for a Type A package when subjected to accidental damaging effects in excess of those experienced in the appropriate regulatory test. This document is not concerned with situations where very high doses may result from extremely unlikely events. It is concerned with normal situations and events resulting from foreseeable traffic accidents. In transport it is accepted that during handling and movement of packages various mechanical and thermal conditions could threaten the integrity of a package. The level of safety in transport is provided by combinations of many requirements, the major combination of which is the quantity and form of radioactive material being transported and the required standard of packaging. As an example, certain materials of very low specific activity may require minimal packaging since their release in any situation will not produce a significant hazard. High activities of irradiated nuclear fuel on the other hand require a high level of packaging integrity such that accident conditions will not result in undue effects.

Although this document is primarily concerned with optimization it is necessary to clearly understand the role of optimization in decision making and the fact that it is only one part, however important, of the system of dose limitation.

2. GENERAL PRINCIPLES

2.1 Role of Optimization and Decision Making Levels.

Generally speaking, optimization can be considered both as:

- a part of a system of dose limitation (a general principle), and
- an input into the entire decision making process.

It may be that optimization in a particular circumstance is a very simple process (an integral part of the decision process providing structured radiation protection inputs to decision making). Often intuitive judgements by radiation protection staff or health physicists are adequate. However for situations such as major policy decisions it may be necessary to formally optimize a complete system requiring detailed data and quantitative analysis.

In transport optimization has a role in:

- the preparation of the standards for the safe transport of radioactive materials, and

- the preparation of the operational requirements for the implementation of such standards.

Radiological protection considerations are only one input to decisions on transport. Comparisons on the basis of radiological impact and financial cost can indicate which options are preferred from a radiological protection viewpoint, other factors, such as political considerations may enter into decisions.

The link between such political considerations and optimization in the decision making process, as well as the use of quantitative methods such as cost benefit analysis within the framework of an optimization process will be depicted in more detail in section 2.3.

Before going further in the description of the methods it is necessary to point out that various regulatory bodies and organizations involved in the transport of radioactive material are in a position to perform optimization analyses. Clearly one can distinguish several levels at which optimization is possible. Assuming that the higher level organization performs the optimization of radiation protection assessment of the transport system, the choices made at this upper level must then be considered as constraints for applying optimization at lower levels.

First one must consider the preparation of standards at an international level. The Transport Regulations (Safety Series No. 6) contain requirements related to package design and testing. As an example, limits are provided on quantities of radionuclides that may be carried in a particular type of package and maximum radiation levels are given for packages. Mathematical models and a selection of representative assumptions have been used to determine such values and, in the absence of realistic data, conservative assumptions are often used. The Regulations are subject to regular review and revision where both the models and the requirements are carefully considered. There is often a desire to improve or develop the mathematical modelling and also a view that the present values have provided the basis for the safe transport of radioactive materials. Optimization can have a role at this stage in taking the present values and looking at the advantages and disadvantages of changes in a quantifiable manner. Amendments to test specifications could likewise be subject to optimization such that the benefits and disadvantages of change could be considered. The optimization process will always be subject to some constraints. Individual dose limitations for workers and the public are clearly constraints and source upper bounds may be imposed on a particular application such as transport.

Secondly, within a given country, the regulatory authorities have the possibility of reinforcing the international standards. The approval of a package design is subjected to a careful analysis of its safety performances. Measures might be requested that go beyond the IAEA standards. Optimization analysis, where all the criteria are clearly set in evidence, can provide valuable information to guide decisions of this kind.

At yet a lower level, in many countries, local or regional authorities do have the power to define compulsory routes and schedules for transit. For example, the US Department of Transportation (Washington, DC) has prepared "Guidelines for Selecting Preferred Routes for Highway Route Controlled Quantities of Radioactive Materials". Here again optimization analysis can provide information to guide decisions on the need for routing restrictions. Furthermore, in these cases, both normal and accident conditions of transport could be considered.

But regulatory levels are not the only ones, the nuclear industry still has many possibilities when designing materials, choosing routes and transport modes, and defining protection measures. The optimization can be performed here at an inter-company level. Interorganizational cooperation already exists in many areas; for example in the case of transport of irradiated fuel, electricity producers, carriers, reprocessing facilities and designers of the packages have worked together towards a "best" package design and associated transport system. Transporters and designers have also to choose among safety options about which they have the full power of decision. Indeed it appears that at all management levels, optimization of radiation protection procedures can be of help. According to the decision making level, the area of application can be more or less restricted (see 2.2), and the technical tools more or less sophisticated but the general procedure will remain the same (see 2.3).

2.2 Areas of application

2.2.1 General

Optimization of radiation protection can be applied to transport as a whole but it can also aim to solve problems encountered in some of the constituent parts of the transport system. When doing so, one must be aware that independently performing partial optimizations does not guarantee that the transport as a whole is optimized. However in practical applications the analyses are very likely to be partial and will deal with specific areas. Very often, fortunately, there are no interdependencies between these areas and therefore the difficulty mentioned above will disappear. In any case, the boundaries of the system under study must be clearly defined at the start of the optimization process (see 2.3).

The analyses can be performed in order to answer different questions, raised by different people. Since these may correspond to different areas of concern, the incentive for the optimization can thus be different. For example, the incentive might be the design of a new container, it might be a concern about the level of exposure of the population, or it might be a desire to assess the need for a new testing requirement. These questions can be grouped under the headings given in the following sub-sections.

2.2.2 Population involved

The optimization process can aim to determine the lowest reasonably achievable collective dose to a given population, from all transport activities. As in other cases of radiation protection, this population can be either workers, the general public, or both. Concern about the general public due to transport activities has already given rise to risk assessment studies [for example, NUREG-0170(6)]. In transport there are many workers involved who have limited or no contact with radioactive materials. The provisions providing for the radiation protection of individuals in the transport industries will depend upon the work involved and the particular role of the individual.

2.2.3 Global approach of the transport system

Optimization is applicable in the setting of standards and specifications and in their subsequent application. In this field must be included all optimization actions linked to regulatory requirements.

The Transport Regulations contain requirements as follows:

- activity and fissile material limits,
- preparation requirements and controls for shipment and for storage in transit,

- requirements for radioactive materials and for packagings and packages,
- test procedures, and
- approval of administrative requirements.

The maximum external radiation levels imposed on packages at various locations, established by regulations, are possibly areas most appropriate to an optimization procedure. It is known that most packages do not approach these levels and are often orders of magnitude lower. There are however some packages transported with radiation levels close to the maximum. For such packages, it should be possible to separately optimize relative to package contents, extent of shielding, and even handling arrangements (see, for example, reference 7), given that the data are available. The benefits of a standard system may however be overriding.

In principle each regulatory requirement could be reviewed and be subjected to an optimization procedure. In practice the efforts involved must be commensurate with the results expected. Certain areas may lend themselves more readily to such an analysis, for example, external radiation levels and quantities of radionuclides.

The processes of periodic review and revision of the Transport Regulations, Safety Series No. 6, together with the guidance material provided in Safety Series No. 37 help to ensure that exposures from the transport of radioactive materials are kept as low as reasonably achievable. Although it is recognized that considerable costs may be involved in regard to areas such as package design, construction and testing requirements, optimization in these areas may provide valuable results. In this regard, optimization in some of these areas could be handled at the international level, whereas other areas might be left to the responsibility of the countries concerned or dealt with by the help of bilateral negotiations.

Some questions which are not necessarily of a regulatory nature need also to be optimized at the level of the whole transport system. Among these is for example the case of policies for transport modes and the associated alternatives of train, road, air or water transport. Another possible area of application is the tracking of packages in transit. Clearly very close tracking is often impossible but information on certain movements is also desirable.

2.2.4 Elements of transport

It is in the elements of transport that optimization analyses have already been performed, both on normal and on accident situations. Optimization can be more easily applied in this field. Some studies have addressed all the elements of transport whereas others have dealt with specific parts.

The constituent parts of transport which are more easily subjected to the optimization process are:

- Selection and design of packaging (for a given product)
- Design of plant for loading (generally also for a given product)
- Maintenance and repair
- Preparation for transport
- Transport
- Storage-in-transit

The optimization process will often be used for a particular type of radioactive material (for example, irradiated fuel, plutonium, radioactive wastes) and the study would encompass the design alternatives, the choice of the transport mode, the routing and the handling operations. This is clearly evident from existing risk assessment studies as for example references 6 to 17. Studies which are not product-linked include those associated with routing and more specifically those concerned with transit through tunnels.

The design of the plant for loading and unloading packages is suitable for optimization procedures. Information on radiation exposures and on costs of plant and staff would be required for such a study.

Handling operations vary from simple "hands-on" procedures to the use of remotely operated lifting mechanisms. The radiation protection element is readily quantifiable and the costs of alternative procedures can be easily identified. This an area where a small effort in optimization may achieve substantial rewards.

Routing is a topic that is being widely discussed. It is possible to quantify the costs of different routings and the radiation exposures to workers and the general public from alternative routings. Different modes of transport for the same package will result in different costs and different radiological protection impact. Optimization is clearly possible in this area though care should be taken to address both normal and road traffic accident situations.

2.3 Methods

2.3.1 Optimization in the decision making process

Optimization of radiation protection is a relevant part of a decision making process.

Here, various steps can be identified, including:

- definition of the relevant parameters and boundaries,
- identification of alternative options,
- estimation of the parameters for each option,
- use of optimization technique for the selection of the best option,
- sensitivity analysis; and
- consideration of other factors and final decision.

The entire decision making process can be schematically represented as shown in Figure 1.

2.3.1.1 Boundaries for Optimization

Before beginning the optimization process it is necessary to define the boundaries of the study by a clear definition of the areas of application. For example, it must be decided whether chemical, road-traffic accident traumas and other associated risks are to be considered. Such considerations establish the boundaries for the optimization process.

2.3.1.2 Constraints to optimization

Individual dose limitations for workers and for the general public are absolute constraints for the optimization process. Upper bound values, intended as a percentage of individual dose limitations that may be imposed on a particular application such as transport, in order to

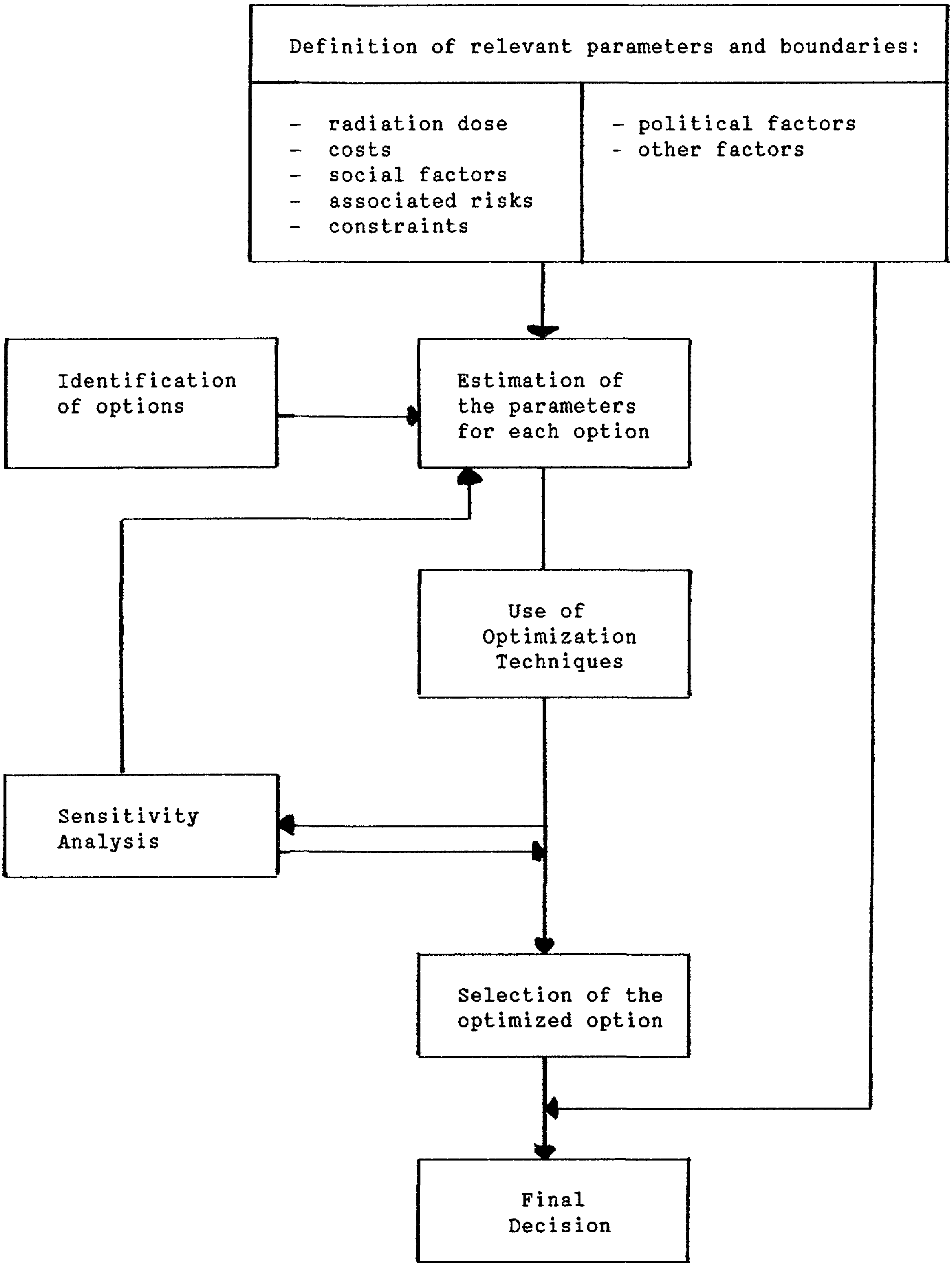

Figure 1 Schematic of the decision making process

allow for the exposure overlap from different practices and to reserve a margin for other unforeseen sources of exposure, may also be a major constraint to optimization. Similarly, international or national standards, such as package requirements set forth in Safety Series No. 6, are constraints, unless they themselves are the subject of the decision making process.

2.3.1.3 Sensitivity analysis

Uncertainties associated with the relevant parameters (for example, radiation doses or costs) and the judgements adopted in the analysis can be significant factors and their influence has to be taken into account, by evaluating the sensitivity of the result to the variation in these factors. The sensitivity analysis allows one to evaluate the stability of the solution, to direct new efforts in order to reduce uncertainties where these appear relevant, to identify crucial factors, to make the process more meaningful and to advise the decision-makers of the level of confidence of the results of the optimization process.

2.3.2 Techniques for optimization

A wide range of techniques is available to optimize radiation protection, and these techniques are suited to different levels of quantitative input. However, the use of a given technique implies, explicitly or implicitly, the making of value judgements. The degree of quantification in the techniques used will vary with the different applications. For instance, designers will tend to use more quantitative techniques for deciding the degree of protection, competent authorities may use either simplified quantitative techniques or conservative qualitative techniques to derive authorized limits, while in daily operation, persons responsible for radiation protection will make reference to simple rules and use intuition and common sense. However, it should be stressed that optimization of radiation protection can be an intuitive process and that quantitative techniques are a substantial aid to optimization, but they are not in themselves the entire process.

2.3.3 Quantitative techniques

Several quantitative techniques can be used for optimization: each of them has advantages and disadvantages and it is often difficult to recommend which technique to use even with regard to a specific situation. Generally the choice depends on the level of the decision-making, on the available resources and on the complexity of the problem. The techniques involved include multicriteria methods, aggregative methods and cost-benefit analysis.

Multicriteria methods compare options in pairs to determine whether one option is preferable to another. A certain number of criteria are defined and evaluated for each option. A relative weight may be assigned for each criterion, if necessary. The value of these methods is that they take account of many criteria, allow the decision maker to be involved in the assignment of relative weights, and are particularly appropriate in dealing with qualitative aspects.

Aggregative methods, instead of comparing options in pairs, such methods allow the direct comparison of all the options simultaneously. Utility functions may be used to express values assigned to the different criteria. These assigned values of the criteria are then combined into a single value which is used to rank the different options.

An important method based on utility functions is cost-benefit analysis. This procedure assumes that all the criteria involved can be expressed in monetary terms and that the parameters are linearly related to such criteria. This method consists of selecting a design option such that the cost of radiation protection (X) and the cost of radiation detriment (Y) comply with the relation:

$$X + Y = \text{minimum}$$

A more detailed description of the method can be found in Annex IV of Safety Series No. 9[(2)] and ICRP Publication 37[(5)].

2.3.4 The monetary value of man-Sv

In some quantitative techniques, such as cost-benefit analysis, it is necessary to assign a monetary value to the collective dose (man-Sv) which is a function of the radiation detriment. The cost of radiation detriment Y is often assumed to be proportional to the collective effective dose equivalent commitment $S_{E,C}$ of the practice.[(5)] If other factors related to the level of individual doses are to be included in the cost of radiation detriment, then an additional component of the detriment can be added, and Y then becomes a function also of individual doses H_i in various exposed groups N_i, so individual dose calculations, the collective doses to the public living close to selected routes should also be assessed.

2.4.2 Costs

2.4.2.1 Costs of radiological protection

The estimation of the cost of radiological protection is, in principle, a straightforward procedure although considerable complexities may arise when detailed costs of packagings, and transport operations have to be considered.

Typically, the cost of radiological protection will involve an initial capital investment combined with complete operating and maintenance costs over subsequent years.[(19)]

2.4.2.2 Costs of detriment

For some optimization techniques, such as cost-benefit analysis, the valuation in monetary terms of the detriment is essential. The concept of radiation detriment has been defined by ICRP as the expectation of harm incurred by exposure to radiation, taking into account not only the probability of deleterious effects but also the severity of the effects. Radiological impact studies often include the assessment of individual and collective doses, and sometimes also the subsequent estimation of numbers of statistical health effects, both fatal and non-fatal. One method of assigning a cost to radiation detriment is to apply cost conversion factors to measures of dose. For example, it is possible to convert collective doses into costs by using a factor in monetary units per man Sv as noted in section 2.3.4.

When assessing investments in radiological protection to reduce levels of public exposure from the transport of radioactive materials, an important factor to consider is the influence of such investments on the dose distribution. If a reduction in public exposure leads to an increase in occupational exposure, then evaluation of the net change in the cost of detriment should be performed. To do this, levels of occupational exposure need to be converted into monetary terms and, as in the case of public exposure, this will require judgements on the appropriate values on the part of national competent authorities. In some countries, current practice is that the multiplying factors used in assigning costs to levels of exposure to the public and to the worker are not the same. In addition, attention should be paid to transfrontier exposures and to ensuring reasonable allocation of resources for reducing exposures. The costing of transfrontier exposures is part of the Agency's programme in the area of radiation protection. A recent publication[18] provides guidance on this problem.

2.4.3 Other factors

In addition to the costs described in Section 2.4.2 above, there are other factors which must be taken into account in the optimization process. ICRP requires that social factors be taken into account.[3] While it is clear that there are further factors which enter into optimization procedures and the decision making process, it is not clear at the present stage whether these other factors can be fully enumerated, detailed and, where appropriate, converted into monetary terms because they may depend on a very specific situation. Where other factors cannot be expressed in direct monetary terms, other methods of approach such as multi-criteria analysis (see Appendix II) may be more appropriate than cost benefit analysis. Examples of other factors to be taken into account within the optimization process are:

Design and operational experience: In design and transport operations consideration of optimization efforts will often be guided by experience. Caution should be exercised when introducing new substantial design changes because of the potential that new risks are introduced.

Other existing regulations: Other existing regulations, which are not necessarily specific to the transport of radioactive materials (for instance, a speed limit for vehicles, weight limits for bridges, and physical protection), may act as practical constraints to optimization efforts and will have to be taken into account.

Social factors: Public opinion and the attitudes of workers, need to be considered in optimization studies. The use of the β-term in the cost-benefit analysis technique may allow such factors to be taken into account.

Optimization procedures may be applied to some accident situations. In such cases, additional factors may need to be considered. For example:

Probability and severity of accidents: There are currently problems in applying the basic principles of radiation protection and specifically the basic system of dose limitation, as set forth in Reference 2, to sources which may go out of control due to accidents or unplanned occurrences. These difficulties relate in part to the need to consider the probability of an event occurring, the probability of exposure as a result of that event and the magnitude of the resulting consequences. This is particularly the case when dealing with transport accidents. For a transport accident, the relevant parameter is risk, which is defined for the purposes of this document as the product of the probability of the event and the resultant radiological consequences.

It is noted however that risk is used elsewhere with several different connotations and definitions. For example, Safety Series No. 9[(2)] defines risk as the individual probability of harm, i.e., it is "proportional to the dose equivalent at low doses and dose rates" (see page 141 of Reference 2). Other documents have used risk in a very general sense, or as equivalent to consequences alone. In some of these definitions, the term incorporates aspects related to the perception of importance for various outcomes, and even of attitudes to the source of the risk.

Furthermore, for the field of radioactive waste disposal the ICRP established a Task Group in 1982, and the results of this Task Group are contained in Reference 20. This report suggests that the difficulty of applying a system based on dose limitation can be overcome by moving to a system based directly on risk, in which the probability that someone is exposed to the dose and the probability of harm from that dose are combined to give the overall risk. This can then be compared with limits on the risk analogous to current limits on dose.

Thus, until the issue of a standard definition of risk and the method of applying it in radiation protection is fully resolved, it was decided to use the definition of risk noted above which is commonly used in the transport field.

<u>Economic and environmental impacts:</u> As a consequence of an accident, contamination of the environment may occur leading to the possible contamination of soil and water resources. Additional economic impact may result from the loss of use of property or agricultural resources.

It should be stressed that, for transport purposes, the packaging requirements which are graded to the quantity of material involved are such that, even in accident situations, radiation doses are not likely to be high and the impact on the environment is likely to be very small, except for some accidents of very low probability of occurrence which may be considered as extremely unlikely events.

3. APPLICATIONS

3.1 Basic requirements

To fully understand the scope of the optimization process, some possible applications of the process will be indicated. These, together with the specific examples in Appendix V, should provide a fuller view of the potential value and impact of optimization. Here the emphasis will be on problems which are, or could be, amenable to quantitative solution. The scope of the applications is represented in the schematic Table 1. Optimization activities may occur within the divisions indicated in Table 1 or be common to several of the sub-divisions. For example, individual doses to workers may be part of an optimization process involving collective dose assessment in incident free transport operations.

TABLE 1

Applications Scheme

Scenario/ Exposed Groups	Radiation Dose		Methods	
	Individual	Collective	Measurement-based	Analysis-based
Incident Free				
Workers	X	X	X	
Public	X	X		X
Accidents				
Workers	X	X	X*	X*
Public	X	X		X

* Either measurement-based or analysis-based

It is certainly possible, and indeed frequent, that optimization is undertaken on a qualitative or semi-quantitative basis based on the experience of the person designing or specifying the process, package, or operation involved. It is not expected that this process would be replaced by the technique presented here. Simpler problems would still be handled best by exercise of judgement but more complex problems would benefit from the increased structure of a formal optimization activity, whether or not it was decided by qualitative or quantitative means.

The application of optimization is a process involving the collection of significant data before any meaningful analysis can begin. These data relate to both the radiation doses received in the situations under study, the associated cost data and other considerations involved, and appropriate criteria included in reaching on optimal solution. The principal sources of the dose data are direct measurement of dose received in existing operations, measurements within the framework of test operations combined with time and motion studies to build a more complete exposure scenario, analysis-based techniques that are often known as risk analysis, or a combination of these methods.

Because optimization is frequently a choice among distinct and separate alternatives rather than distinguishing a single combination of a set of continuous variables which achieve an optimal solution, it may be necessary to develop exposure data for all possible alternatives. Similarly the data for the other variables that are to be taken into account must be obtained for all the alternatives to be examined. When a simple cost and radiation dose situation is involved, the cost information may be relatively straightforward. When more complicated multi-attribute optimization is involved each variable may be developed for each alternative. This may lead to significant increases in data needs.

To complete this process data must be developed to support decision criteria. Here the data requirements relate, for example, to the monetary value to be placed on preventing a health effect for a simple cost-benefit optimization problem. In more complicated cases, such as the possible trade off of dose between workers and the public, more complicated criteria related data must be developed to define achievement of an optimal choice of alternative. Value judgements will often be required in practice.

3.2 Analytical Assessment

Of central importance in the optimization process are the health effects which are to be made as low as reasonably achievable (economic and social factors considered). In principle these effects may be obtained for incident free, normal and accident conditions of transport through direct measurement, but in practice many normal exposures and most accident exposures will only be obtained through the use of analytical assessment methods. While such methods, as for example the Agency's code, INTERTRAN[21], will, therefore, hold a key role in optimization, it is clear that the use of risk analysis results in optimization studies must be subject to reservations concerning two related attributes, which are: (1) comparative accuracy, and (2) sensitivity to input data. In the first case, a problem may arise if the results for all alternatives treated in an optimization exercise are not based upon the same exposure scenarios. This allows the possibility that scenarios in the analytical model are subject to different degrees of conservatism. In such a case the differences among alternatives may not be real, but may be an artifact of the estimation technique. The second qualification, that of sensitivity to input data, results from the analytical model being very sensitive to specific input parameters. This means there is a great need for accurate estimation of a parameter. If very precise data are available, this presents no problem, but frequently only relatively poor data are available for many parameters in such an analysis. Proper awareness of model sensitivity and demonstrated sensitivity/error analysis documentation is desirable.

3.3 The cost and extent of the process

Caution has to be taken that the cost of the optimization process itself remains commensurate to the potential savings in detriment. The first step, that of the identification of options should always take place. The extent of the following steps would then depend on the cost of the exercise, and the returns to be obtained from the completion of the optimization process. If the cost of performing the optimization process is greater or equal to the potential savings, then the optimization should be qualitative.

3.4 Radiological protection considerations

The ICRP recommend, for radiation protection purposes, that the number of health effects in exposed individuals and the herditary effects in descendants are assumed to be directly proportional to the collective dose in an irradiated population. The measure of collective dose can therefore be used to represent the radiation-induced health detriment in a workforce and, when the size of that workforce is known, as a means of estimating average individual detriment. However, workers occupationally exposed to radiation are often individually monitored and those consistently receiving more than the average may regard the collective dose as secondary to their individual level of exposure. The relative importance given to individual and collective doses needs careful consideration and judgements on this factor are often reflected in decisions taken by management. For example, one way of achieving reductions in the individual doses is to distribute work involving high exposures among a larger number of workers. The reductions in individual doses are then achieved at the cost of increasing the number of workers exposed which, because of variations in level of skill or increased access times, may result in an increase in the collective dose and hence in the total health detriment to the workforce required to accomplish a particular task. Conversely, there are circumstances, particularly with some maintenance and repair work, where the use of highly skilled pesonnel can result in a significant reduction in the collective dose but with higher individual doses and therefore higher radiological risks to those skilled workers. This trade-off between individual and collective doses is, of course, constrained under all normal operating conditions by the specification of annual dose limits for radiation workers.

3.5 Transport Environment

Public concern over exposure from normal transport or from potential accident situations during transport is a factor separate from the optimization procedure. Such concern may well influence the final decision but should not affect the optimization analysis. Reference 17 makes the point that accidents involving transport vehicles can only lead to significant public radiation exposures when their severities are sufficient to degrade the shielding and containment capabilities of a package. Accidents can produce significant exposure only when an event occurs which produces a release of contents or loss of shielding. Very large doses may be possible as a result of very unlikely events while higher frequency accident events generally produce little or no radiological impact to the public. A quantity which represents all such exposures is risk (defined as the sum over all events of the effect of an event, times its probability). This document does not consider the very unlikely event scenarios.

In order to perform optimization of radiation protection in a situation where a source may get out of control, it is necessary to perform probabilistic risk assessments. However, such risk assessments must be coupled with cost effective analyses in order to constitute optimization of radiation protection. Reference 22 describes such an assessment in the application of ALARA (as low as reasonably achievable) principles to the safety of radioactive material transport. A schematic representation of the risk assessment portion is given in Figure 2 (see Reference 22).

Examples of complex probabilistic risk assessments of radioactive material transport are embodied in reports such as References 23 and 6. Reference 23 provides an analysis of the qualification criteria for small radioactive material shipping packages. This was a statistical study which examined the maximum or near-maximum environmental stresses produced in road, rail and aircraft transport accidents. Reference 6 utilized data such as these as part of step 2 of Figure 2, modeled transport of various radioactive materials in the US, modeled package failures and provided a comprehensive picture of the risk associated with radioactive material transport in the US. Neither of these constituted optimization of radiation protection.

3.6 Elements of Transport

In the sections that follow a general view is provided of the kind of optimization problems that are likely to be seen in transport together with an indication of the exposed populations involved and the potential trade offs associated with the optimization process. While the principal emphasis is on a relatively simple cost-benefit optimization process, it is clear that inclusion of other factors requiring more complex analysis is possible and in some cases may be even more desirable.

3.6.1 Design

The purpose of this subsection is to provide guidance on the application of the principles for optimization of radiological protection when designing packagings/packages for the transport of radioactive material. Attention is focused on controllable design variables rather than uncontrollable design variables and fixed requirements as provided in IAEA Safety Series No. 6[1] (Regulations for the Safe Transport of Radioactive Material).

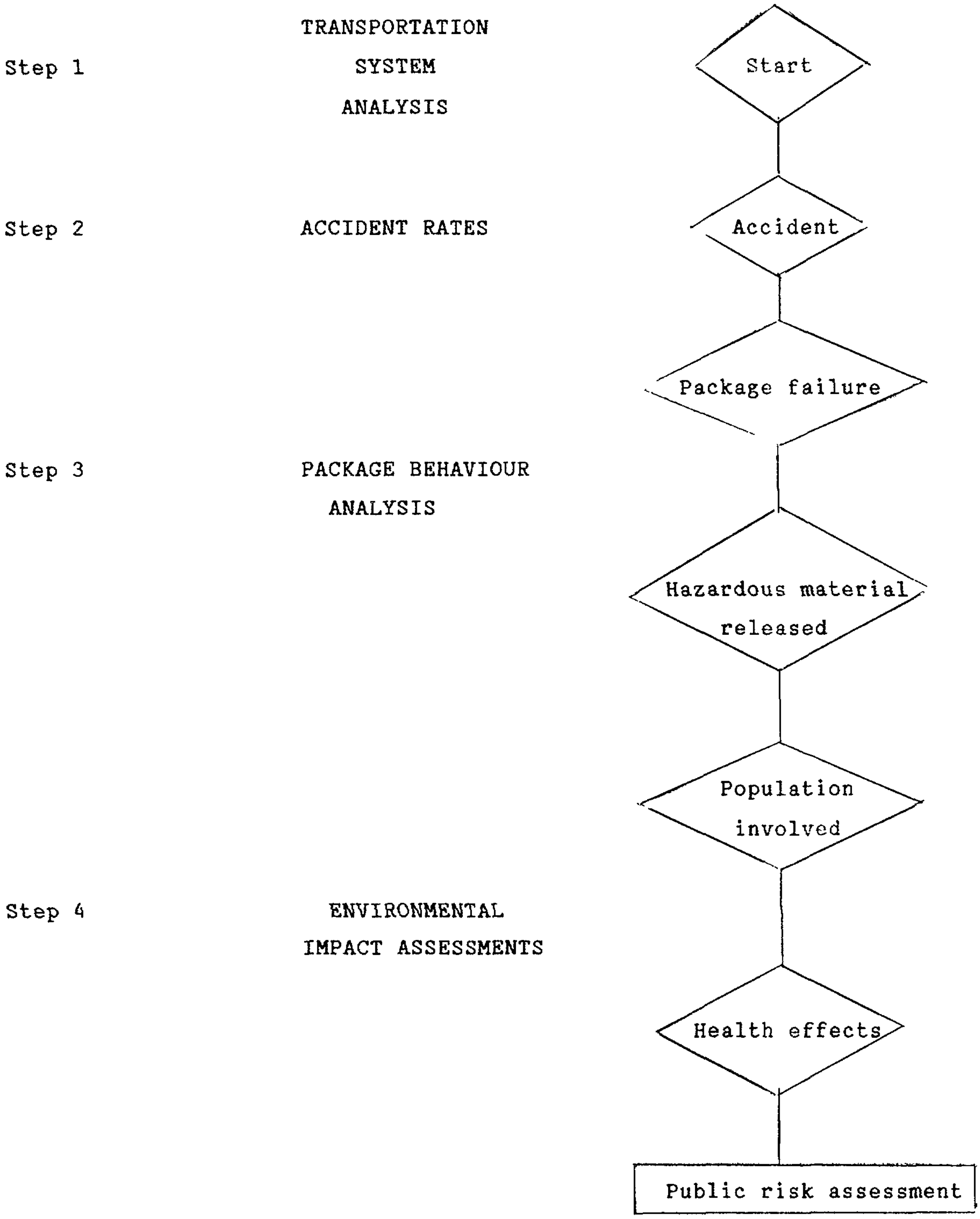

Figure 2. Schematic for Transport Accident Risk Assessment

It should be noted that optimization of radiation protection in design is part of a process which is mainly based on technical judgement and experience. Therefore the guidance may be a substantial aid to the process of optimization, but does not constitute the process itself.

Care should be taken to make such considerations as early as possible during the design:

- to avoid additional costs and delays,
- to take full account of the potential impacts on other parts of transport operations, e.g. maintenance, handling, preparation for transport and storage in-transit, and
- to take into account other relevant applications, for example gammaradiography.

The optimization process may be subdivided in several interactive steps as follows:

3.6.1.1 Specification of the design problem

The specification of the design problem is a preliminary stage aimed at drawing the most appropriate borderline between what should be considered within or outside the framework of the optimization process. This delineation is sometimes not straightforward, due to various interacting factors.

It may be useful to consider some alternative safety design solutions in order to increase the number of design protection options available for normal operations.

Some procedures reduce collective dose, for example, the introduction of alternative materials, but may increase the cost of materials and fabrication, and hence the cost of the package and possibly the operational costs. The balancing of these factors is an important optimization consideration.

Potential conflicts between optimization of radiation protection, safety and physical protection must be reviewed. The importance of past experience must be stressed as it may altogether help to define new solutions and reject others.

The designer should be fully informed on the future use and handling procedures of the package.

3.6.1.2 Estimation of protection costs, detriment and other factors

The optimization process requires to some extent a subjective estimate of the various components attached to the design options. Caution should be used however since some of these components (such as the influence of the option on reliability or safety, on the organization of work, potential increase of dose or operating cost with time) cannot always be fully quantified. However these other factors are often very important in the overall judgement of the option and should always be considered even though this may only be subjective. The existence and importance of such other factors may in certain cases influence the choice of the quantitative technique to be used.

3.6.1.3 Sensitivity analysis (see also section 2.3.1.3)

Two factors of variability of the results need to be taken into account: the uncertainty of the inputs (e.g. costs, detriment, calculational models) and the value judgements incorporated in the analysis (e.g. weighting of the various criteria). It is therefore desirable to evaluate the sensitivity of the solution to variation in some or all of these factors.

3.6.1.4 Examples with regard to package design

- Additional costs for providing readily decontaminated external package surfaces as well as for providing outer layers of the package capable of preventing the collection and retention of water may be offset against reduced radiation doses resulting from decontamination.

- Packagings/packages used in large numbers for the transport of radioactive material in industry, medicine and research may be so designed that the use of an appropriate overpack can reduce the radiation dose during handling.

- Packages, in particular gammaradiography devices, may have different dose rates at the different parts of the surface. Costs for providing a handle or handles such that the highest dose rate surfaces of the package are furthest away from the body or hands may be offset against reduced radiation doses during handling.

- Additional costs for designing and manufacturing packages capable of being remotely handled may be offset against reduced radiation doses resulting from handling.

3.6.2 Maintenance and Repair

According to para. 209 of Safety Series No. 6,[1] it is required that packagings be maintained in good condition so that they continue to comply with all relevant provisions of the Regulations. This subsection focuses on the processes of maintenance and repair, keeping in mind that the work is done on an empty packaging which may be internally and externally contaminated and that the contamination may be fixed as well as non-fixed.

The execution of a maintenance or repair programme may be preceded by an optimization evaluation including:

- the amount of contamination,
- the cost of decontamination to specific levels,
- the individual doses and collective dose resulting from the decontamination, and
- the individual doses and collective dose resulting from the maintenance/repair, with and without decontamination.

3.6.3 Preparation for Transport

Preparation for transport of a consignment of radioactive materials is carried out at the point of despatch, so that the only exposure occurring in this process is occupational exposure. However, the way a consignment is prepared may well have an influence on both the exposure of transport workers and the general public during the subsequent phases of the shipment. It is therefore of importance to make the preparations for transport with the subsequent exposure conditions in mind. A well established knowledge of these conditions is a prerequisite for optimization to be adequately achieved during the preparation stages.

Preparation for transport comprises several elements of importance for radiation protection, such as selection of packaging, loading and closing of that, in general,

$$Y = \alpha\, S_{E,C} + \beta\, \Sigma_i\, N_i f(H_i)$$

where α, β are factors for converting levels of dose into monetary terms.

With regard to international applications of the above equation, an IAEA document provides a recommended minimum value of α for evaluating transboundary radiation exposure.(18) International guidance for the value of β is not currently available. The values assigned to β can differ by orders of magnitude between different countries and for different applications.

2.4 Data Requirements

2.4.1 Radiation protection data

Transport of radioactive materials occur is both nationally and internationally, and it is important that the radiological protection impact be considered in both these areas. Information is required on the following:

- individual doses* to exposed workers (dose ranges and maximum doses);
- individual doses to members of the public (maximum doses for the individuals of the reference group);
- collective doses** to exposed workers; and
- collective doses to the general public.

A few transport workers receive radiation doses which require individual monitoring. However, most transport workers receive low doses and in these cases direct measurements are generally not possible. Thus, in order to assess the full impact of the transport of radioactive materials it is often necessary to use mathematical models.

For members of the public because measurements for individuals are difficult due to the very low doses involved, mathematical modelling is essential. The input for these models comes from radiation measurements in the environment close to the packages and from published data. In addition to

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* Individual dose is an abbreviation of individual effective dose equivalent
** Collective dose is an abbreviation of collective effective dose equivalent

package, decontamination, and determination of external dose levels and contamination. Some of these elements have a bearing on radiation protection conditions at the site of preparation only, whilst others have an additional bearing on radiation protection conditions at other locations. There are thus two aspects involved in the optimization considerations, the in-plant and the combined in-plant and off-plant aspects. The combined situation is most important for the transport operations, whilst the in-plant situation is expected to be covered by the plant operational radiation protection programme.

Selection of packaging, which inherently determines the resulting external radiation levels, is clearly appropriate for optimization. A packaging providing additional shielding, or generally increasing the overall size of the package, will increase the mass or volume of the package and thereby often may increase the cost of transport. Use of such packaging could also, however, result in reduced external radiation levels. Optimization is an appropriate tool for reaching the balance between the level of radiation protection afforded to workers and to the general public and in the costs thereof. In striking this balance the boundary conditions on package characteristics and on external radiation levels provided by the relevant transport regulations must be adhered to.

Packaging selection and specific operational and/or physical controls during loading are likely to influence the radiation protection conditions during the various phases of transport. Since this influence may well be difficult to assess in quantitative terms, formal optimization may be difficult to achieve. There are, however, other optimization options available, and in this case in particular those based on experience and sound professional judgement, lend themselves to this application.

Decontamination of the external surfaces of a package is an operation which, in some cases, involves considerable occupational effort and exposure. Because of the complex nature of decontamination, both the work methods and the desired contamination level need to be carefully considered in the light of occupational exposure involved during decontamination and the reduction of potential dose accrued by transport workers and the general public during the subsequent phases of transport. An optimization procedure could readily be applied to determine the appropriate work method and desired level in the decontamination operation. Again, the boundary conditions relative to surface contamination stipulated in the relevant transport regulations must be adhered to.

3.6.4 Package Handling

The handling of packages clearly involves occupational exposure. Dependent on how and where packages are handled exposure of the general public may also occur. Public exposures can occur during certain handling operations, for example the loading and unloading of vehicles at places where the public has access.

The handling procedures involved in transport depend upon a number of factors including the numbers of packages involved, their weights and sizes, the facilities available and the mode or modes of transport. Limited data are available from various countries on the occupational doses due to the handling and movement of radioactive packages. In general, collective doses are low but in some cases individual transport workers receive high doses but still within the limits. A review of exposure data from various countries is given in Appendix IV.

The handling of radioactive packages is an area where small changes in operating procedures may lead to savings in occupational doses. Rigorous optimization procedures may not be necessary. Deliberate consideration and sound judgement may be all that is required. For example, in the United Kingdom a study of occupational exposures from transport(24) showed that 87% of the radiation dose to workers during the transport of radioactive materials was due to the need to transport radioisotopes for medical and industrial use. A subsequent UK study on the transport of technetium generators(7) has shown that the use of distant handling of such packages significantly reduces occupational doses for a small expenditure on equipment.

3.6.5 Transport

During a normal transport operation of a consignment of radioactive material, exposure of the general public occurs during the movement and delivery phases of the transport operation. During the movement phase the consignment may be transported on the same aircraft, vehicle or vessel that carries passengers. Therefore, transport by air, by rail and by sea are examples of situations where passengers may come or be accommodated in close proximity to such consignments. The parking of vehicles in public places can also lead to exposures of members of the general public.

With regard to protection from exposure in a transport operation of a consignment of radioactive material, consideration may be given to optimization within the limits of the regulations amongst the following parameters: consolidation of the packages for rapid handling, location of the stowage area within a cargo space, increase of segregation distances, use of intervening space for shielding by other cargo, provision of additional stowage area shielding. Each of these measures may have direct or additional costs such as for additional space or material and indirect costs such as time spent or operational complexity which may be traded off against the decreased dose.

Routing of shipments also has optimization applications in transport operations. For instance, in the United States there are routing regulations that require the carrier to use a route that presents a risk to the fewest persons and minimizes transit times. For certain consignments preferred highways are to be used and interstate urban circumferential or bypass routes must be used. Optimization procedures applied to time and distance (which control cost and exposures) and populations exposed, considering both normal and accident situations, can be applied within such requirements.

3.6.6 Storage-in-transit

With regard to protection from radiation exposure for a consignment of radioactive material during storage-in-transit, generally the procedures and measures outlined in subsection 3.6.5 should be applied, but suitably adapted to storage-in-transit situations.

Storage-in-transit may involve customs operations and procedures to be applied to an undeliverable consignment of radioactive material as specified in paragraphs 483 and 484 respectively of the IAEA Transport Regulations, 1985 Edition(1). Although compliance with paragraph 483 or 484, as appropriate, will reduce the possibility of exposure to radiation, the greatest care should be exercised when carrying out related tasks.

Although it might be highly desirable to load consignments of radioactive materials onto the conveyance as soon as possible rather than store such consignments in waiting areas, circumstances may not permit this and, therefore, a specially isolated or shielded area may be designated for storage in transit, thus ensuring that workers and other personnel will be less exposed to radiation during normal handling and loading operations of other cargo.

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APPENDIX I - GLOSSARY OF TERMS

absorbed dose, D: The quotient of $d\bar{\epsilon}$ by dm, where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm:[12]

$$D = \frac{d\bar{\epsilon}}{dm}$$

Unit: $J.kg^{-1}$

The special name for the unit of absorbed dose is gray (Gy):

$1 \text{ Gy} = 1 \text{ J kg}^{-1}$

(Although gray is a synonym for joule per kilogram, it is to be used only for absorbed dose, kerma, and specific energy imparted).

In practice, the former special unit rad is still sometimes used.

$1 \text{ rad} = 10^{-2} \text{ J.kg}^{-1}$

ALARA: An acronym for "as low as reasonably achievable", a concept meaning that the design and use of sources, and the practices associated therewith, should be such as to ensure that exposures are kept as low as is reasonably practicable, economic and social factors being taken into account.

collective effective dose equivalent : See dose equivalent.

competent authority: An authority designated or otherwise recognized by a government for specific purposes in connection with radiation protection and/or nuclear safety. For transport of radioactive material, competent authority shall mean any national or international authority designated or otherwise recognized as such for any purpose in connection with the Regulations for the Safe Transport of Radioactive Material.

contamination, radioactive: The presence of a radioactive substance or substances in or on a material or in a place where they are undesirable or could be harmful.

cost-benefit analysis, differential: A procedure for optimization of radiation protection used to determine the point at which exposures have been decreased so far that any further decrease is considered less important than the additional necessary effort required to achieve it.

cost-effectiveness analysis: A procedure which is used to determine the most effective protection obtainable from fixed resources or, alternatively, the least expensive protection for a given level of exposure.

critical group: For a given radiation source, the members of the public whose exposure is reasonably homogeneous and is typical of individuals receiving the highest effective dose equivalent or dose equivalent (whichever is relevant) from the source.

decontamination: The removal of radioactive contaminants with the objective of reducing the residual radioactivity level in or on materials, persons or the environment.

detriment: The mathematical expectation of the harm (damage to health and other effects) incurred from the exposure of individuals or groups of persons in a human population to a radiation source, taking into account not only the probabilities but also the severity of each type of deleterious effect.

dose: In this document an abbreviation of effective dose equivalent.

dose equivalent, H: The product of Q, N and D at the point of interest in tissue, where D is the absorbed dose, Q is the quality factor, and N is the product of all other modifying factors as specified by ICRP:

$$H = QND$$

ICRP has assigned the value 1 to N.

The unit for both D and H is $J.kg^{-1}$. The special name for the unit of dose equivalent is sievert (Sv):

$$1 \text{ Sv} = 1 \text{ J.kg}^{-1}$$

(Although sievert is a synonym for joule per kilogram, it is to be used only as a unit for dose equivalent).

In practice, the former special unit rem is still sometimes used:

$$1 \text{ rem} = 10^{-2} \text{ Sv} = 10^{-2} \text{ J.kg}^{-1}$$

effective dose equivalent, H_E: A quantity defined as

$$H_E = \sum_T w_T H_T$$

where H_T is the mean dose equivalent in an organ or tissue T, and w_T is a weighting factor specified by ICRP.

collective effective dose equivalent: For a given source, the integrated product of effective dose equivalent and number of individuals in the population:

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

where $P(H_E).dH_E$ is the number of individuals receiving an effective dose equivalent between H_E and $H_E + dH_E$ from the given source.

Alternatively,

$$S_E = \sum_i \bar{H}_{E,i} \; P(\bar{H}_{E,i})$$

where $P(\bar{H}_E)_i$ is the number of individuals in population subgroup i receiving an average dose equivalent of $H_{E,i}$.

Unit: man·sievert.

effective dose equivalent: See dose equivalent.

exposure: A term used in this document in a general sense to describe irradiation of persons or materials. Exposure of persons to ionizing radiation may be either:

(a) external exposure, irradiation by sources outside the body, or

(b) internal exposure, irradiation by sources inside the body.

The term occupational exposure refers to exposure of a worker received or committed during a period of work.

monitoring: The measurement of radiation or activity for reasons related to the assessment or control of exposure to radiation or radioactive material, and the interpretation of such measurements.

multi-criteria method or analysis: A procedure for optimization of radiation protection where options are compared in pairs to determine whether one option is preferable to another.

non-stochastic effects: Radiation effects for which a threshold exists above which the severity of the effect varies with the dose.

optimization (of radiation protection): See ALARA.

package: Package means the packaging with its radioactive contents as presented for transport.

packaging: Packaging means an assembly of components necessary to enclose the radioactive contents completely. It may, in particular, consist of one or more receptacles, absorbent materials, spacing structures, radiation shielding, and devices for cooling, for absorbing mechanical shocks, and for thermal insulation.

quality factor, Q: A factor that weights the absorbed dose, defined as a function of the collision stopping power in water at the point of interest. Values of Q are specified by ICRP [4].

radioactive material: For the purpose of the Transport Regulations, radioactive material shall mean any material having a specific activity greater than 70 kBq/kg (2 nCi/g).

reference group: See critical group.

risk: The sum over all events of the effect or consequence of the event times its probability. (N.B. Risk is used as a general word in different contexts and this may be important; see page 18 of section 2.4.3.)

sievert (Sv): The special name of the unit of dose equivalent.

$$1 \text{ Sv} = 1 \text{ J.kg}^{-1}$$

stochastic radiation effects: Radiation effects, the severity of which is independent of dose and the probability of which is assumed by the ICRP to be proportional to the dose without threshold at the low doses of interest in radiation protection.

upper bound, dose: A dose level established by a competent authority to constrain the optimization of protection for a given source or source type.

APPENDIX II - PROCEDURES FOR MULTI-CRITERIA ANALYSIS

Multi-criteria analysis, as its name indicates, is used for complex cases with numerous factors (or criteria) at stake.(1)

Multi-criteria analysis is not an aggregative method but a comparative one. The aggregative methods combine all the different criteria, representing the relevant factors, into one single value. This procedure may sometimes be difficult to implement, for example:

- when the criteria are too numerous,
- when the criteria are too heterogeneous, and/or
- when the estimation of some criteria is qualitative.

In these particular cases the use of an aggregative method is not recommended and an alternate method must be considered, such as multicriteria analysis, which allows comparison of protection options. Instead of searching for a global valuation expressing the performances of each option, these methods compare in a first step each option i to every other j, in order to evaluate if option i is preferred to option j.

This evaluation is based on two indicators:

- the first indicator is based on the relative importance of the different criteria where option i is preferable or equivalent to option j (taking into account uncertainties when necessary). This indicator reflects the advantage in choosing i rather than j.

- the second indicator concerns the other criteria (where j is in fact preferable to i) and is based on the maximum gap between i and j for these criteria. This indicator reflects the disadvantage in choosing i rather than j.

At the end of this stage, for all pairs of options, an assessment of the two by two preferences is set up. Situations may exist however where two options are too close to be distinguished. In this case there is no preference between the two options.

Then, from these various preferences a selection of one option or the most dominant options is performed by an appropriate algorithm. The method leads to the selection of one, or a few, analytical solutions.

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APPENDIX III - COST BENEFIT ANALYSIS

Cost benefit analysis is one technique for use in optimization of radiation protection. The ALARA procedure finds a compromise between the cost of protection and the health risk.

If the collective dose S is accepted as a good indicator (or criteria) of the health risk, the costs and the collective doses associated with each protection option should be compared to find the best option. If a monetary equivalent for the man-Sievert (collective dose unit) is available, the risk may be changed into its monetary equivalent and the sum of the protection cost found, to establish the total cost.

If the cost of the man-Sievert is called α, the optimum option shall be that which minimizes the total cost:

$$Si^* \Leftrightarrow \text{minimum } (Xi + \alpha\, Si) \text{ or min } (Xi + Yi)$$

where Xi represents the protection cost of option i

Si the collective dose associated with option i

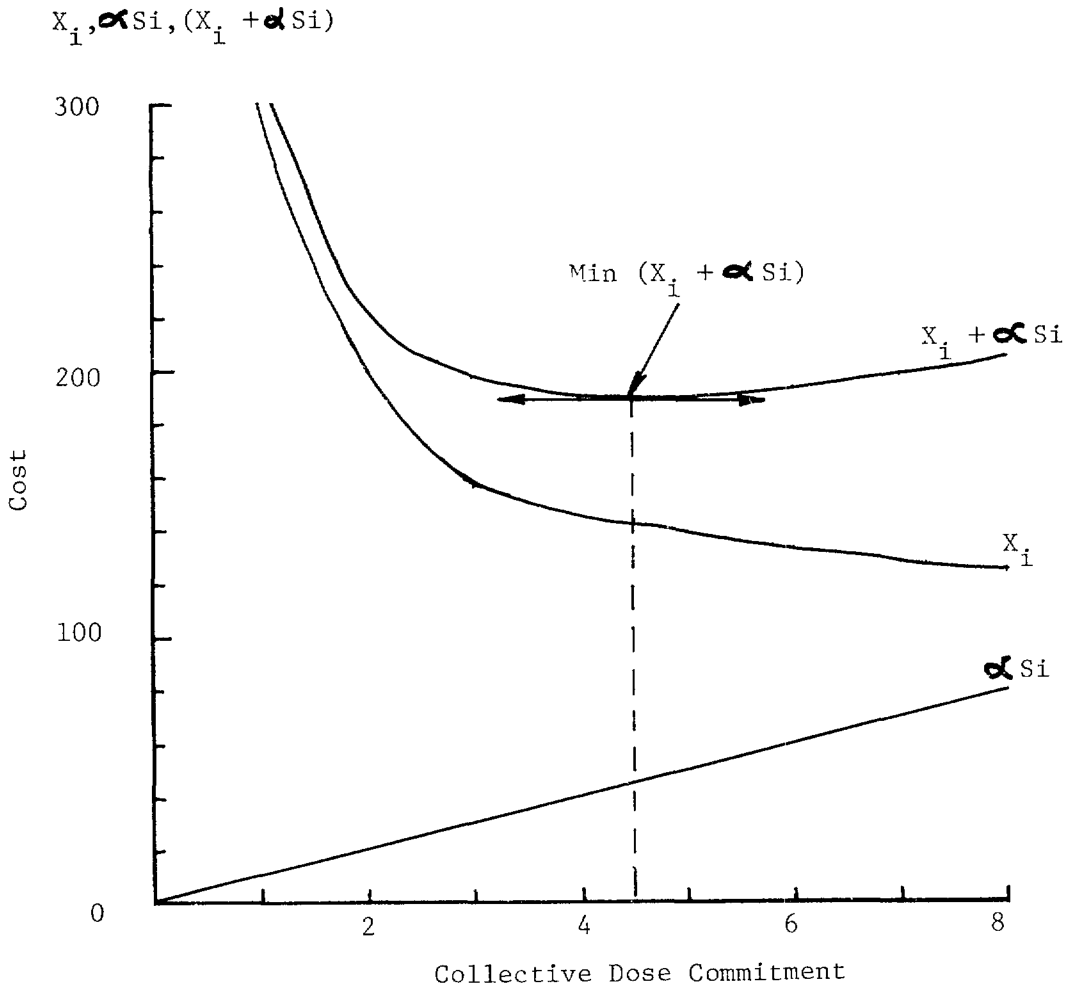
α the cost of the man-Sievert

i* the optimum option

Yi the cost of detriment.

In general this procedure is shown by the following graph where the collective dose associated with each option is shown on the X axis, and protection cost Xi, cost of detriment α and the total of $X + \alpha\, Si$ are shown on the Y axis.

For this hypothetical case ($X_i = 200/Si + 100$; $\alpha = 10$), the optimum dose level is 4.5 and the option to be taken, i*, is that which leads to a collective dose of 4.5 (without taking into account the various uncertainties which lead us to estimate that a range of values from 3 to 6 would be more credible).



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APPENDIX IV - EXPOSURE DATA FOR RADIOACTIVE MATERIALS TRANSPORT

A review was made of data available to an IAEA consultants committee[1] to provide perspective on the individual and collective doses that result from the transport of radioactive materials. These data are summarized in Table I. The data from References 2 through 7 represent values substantiated by dose measurements, whereas the data from References 8 through 11 are analyses based on idealized, and often worst case assumptions. For example, Reference 8 notes that the models are conservative and do not include such ameliorating effects as vehicle structure shielding. Similar conservatisms are present in the analyses described in References 9 and 11. Also, it is noted in Reference 4 that actual measured doses were significantly lower than those calculated in the usual conservative manner. Thus, the data from References 8 through 11 may be higher than actually occurs in transport.

The data from References 2, 6, 9, 10 and 11 represent estimates of collective doses from all transport activities in the UK, France, Sweden and the US. The data from References 3, 4, 5, 7 and 8 represent part of the activities in Italy, India, Japan and the FRG. For example, the shipments represented by the Reference 4 data, which results in a collective dose to workers of 0.34 man Sv represent approximately 15 percent of the total shipments in Italy.

The data from the above cited references show that the maximum individual doses to transport workers is no higher than 10 to 20 mSv/y. In the case of the data from the UK, it is further noted that the individual doses to transport workers in excess of 1 mSv/y occur to an extremely limited population.

Similarly, it can be seen that maximum individual dose to members of the public is very low, on the order of 0.02 to 0.08 mSv/y.

The occupational collective doses for the transport of radioactive materials, for those countries where the data have been verified through measurements, are also low. For example, the collective dose to workers in the UK is only 1 man Sv per year, and to the public is only about 10 percent of this value.

Table I. Summary of Transport Exposure Data from Member States

	TRANSPORT WORKERS		MEMBERS OF PUBLIC	
	Annual Population Dose (man Sv)	Annual Individual Dose (mSv)	Annual Population Dose (man Sv)	Annual Individual Dose (mSv)
Transport of all RAM in UK[2]	1	20 (maximum)	~ 0.1	0.04 (maximum)
RAM Transport in Italy[3]		3.2 (maximum)		
Transport of Radiopharm. in Italy[4]	0.34		0.006	
Transport of Radiopharm. in Bombay[5]	0.014		0.1	
Transport of RAM in France[6]	0.3	20 (maximum)		
Transport of RAM in Japan[7]		0.7 (maximum)		
Transport for Postulated 14 GWe Fuel Cycle in FRG[8]	4.0 to 11.5	3 (maximum)	0.2 to 0.6	0.08 (maximum)
Transport of all RAM in Sweden[9]	0.3			
Extrapolated data for transport of RAM in US (1975)[10]	~ 16		14	
Transport of all RAM in US (1975)[11]	50	9 (maximum)	45	~ 0.02 (maximum)
Transport of all RAM in US (1985)[11]	126	9 (maximum)	127	~ 0.02 (maximum)

It is noteworthy that the US data (Reference 11) provide estimates for individual doses which correspond with the data from other sources, but the collective doses are significantly higher. The reasons for this may be:

1) Conservative estimates on doses as discussed above,
2) The much larger number of shipments for the US, and
3) The much greater distances travelled in the US.

For example, for the UK, Italy and France, a few hundred thousand packages are shipped per year, and these shipments occur over distances of only a few hundred kilometers. In comparison, in the 1985 US analysis (Reference 10), it was assumed that 5.6 million packages will be shipped over distances ranging from 200 to 13,500 km because this study considered the total collective dose resulting from domestic transport as well as imports and exports. Thus the number of packages in the US study is larger by factors of 10 to 50, and the distances travelled by the packages are larger by similar factors. A study of shipments in urban areas in the US was extrapolated on the basis of total TI shipped (Reference 10) and resulted in a factor of three reduction in the values estimated in Reference 11. This illustrates that more detailed assessments and verifications of parameters may be needed.

Two additional studies are worth mentioning here. Measurements of exposures to transport workers resulting from rail transported radioactive material packages were reported in Reference 12. It was found that 71% of the handlers, 100% of the acceptance personnel and 78% of the transport personnel receive annual dose equivalents less than 0.5 mSv. Only 3% of the handlers and 1% of the transport personnel received annual dose equivalents greater than 1.5 mSv, and no transport worker exceeded 5 mSv.

In a study reported to the IAEA as part of a Research Agreement,[13] radiation exposures to transport personnel in France were measured over a four year period. For workers involved with the packing, transport and delivery of approximately 160,000 packages of radiopharmaceutical products, radioactive sources and products for medical analysis, an average annual collective dose of 0.23 man Sv was measured, yielding an average individual dose of 15.5 mSv. The transport of PWR and BWR spent fuel packages resulted in essentially no exposure to workers. The transport of nuclear materials, such as natural or enriched uranium and plutonium in either metal or oxide forms, resulted in average individual whole body doses of approximately 0.25 mSv, with a maximum of 1.3 mSv.

It is hoped that Member States will provide further data on exposures resulting from the transport of radioactive materials. Optimization procedures require a good data base.

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APPENDIX V - EXAMPLES OF OPTIMIZATION IN THE TRANSPORT OF RADIOACTIVE MATERIALS

The concept of ALARA, which is synonymous with the optimization of radiation protection has been in use for some time. As a result, there are a number of examples of optimization applications available in the relevant literature that might be useful as guidance.

Several examples are discussed below and, as needed, some additional comments are included to indicate the important optimization principles involved.

V.1 General example

ICRP Publication 37[1] gives a general example of the optimization of radiation protection in the transport of radioactive materials by road, rail and waterways, and considers both normal and accident conditions. Although the example is not quantitative in nature, it does set out principles for the application of the optimization concept and is reproduced below.

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

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

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

"The calculation can conceptually be extended to an entire network of transport pathways connecting the points of production and use of radioactive materials. Thus, the total detriment associated with the full system of radioactive material transport in the country can theoretically be evaluated. Generally, the transportation between any two points in the system may be achieved through different alternative pathways of transport (air, road, rail or waterway) with which different values of radiation detriment are generally associated owing to the different features of the transport (packaging standards, speed, pathway characteristics) and the different distribution of population. These alternatives generally imply differences in the transport costs due to the different lengths of the alternative pathways, as well as to the type of transport means and the pathway features. If the detriment and the cost associated with each alternative transport network and system considered could be formulated, a theoretical optimization can be performed using the methods described in Section B." (Note: Section B referred to here is Section B of Reference 1.)

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

V.2 Examples involving normal transport

The proceedings of PATRAM '80 held in Berlin (West) and of PATRAM '83 held in New Orleans contain a few papers on optimization in radiation protection. At the Berlin symposium Murphy et al[2] presented a paper on the application of ALARA principles to the shipment of spent fuel and Sutherland[3] gave a paper on an ALARA assessment of spent fuel and nuclear waste transport systems.

Murphy[2] considered various options in transport equipment design. Radiation doses were calculated and converted to costs. The alternative equipment designs were also costed and the following conclusions presented: "Public exposure to radiation from spent fuel shipments is low. Occupational and transport worker doses account for the majority of the total dose. Any efforts to reduce dose should be concentrated in this area. Practices that affect the age of spent fuel in shipment and the number of times the fuel must be shipped prior to disposal have the largest impact on accumulated dose. A policy to encourage a 5-year spent fuel cooling period prior to shipment coupled with appropriate cask redesign to accommodate larger loads would be consistent with ALARA principles. Rerouting shipments to avoid high population density areas will not reduce total shipment dose due to a corresponding increase in occupational dose."

Sutherland[3] did not perform a complete cost-benefit assessment per se, but provided data which could be used in such an assessment. Parametric assessments were performed for cask designs depending upon the age of spent fuel, allowable surface dose rates, and cask radiation shield configurations, and these data were then used to determine the lifetime transportation costs for each configuration. It was then concluded that "(1) some low dose rate cask designs may be oversize or overweight if lead or steel provide the gamma shielding, (2) designing for 5 instead of 10 mrem/h increases the cask weight by about 10% and for 2 mrem/h adds another 10% or more to the weight, and (3) the increased weight of the low dose rate casks results in an estimated $1 to $2 million increase in the cask lifetime transportation costs."

At PATRAM '83 there were 8 papers given on risk analysis techniques and 8 papers presented on risk analysis. Optimization is the subject of only one of these papers, that of Palacios and Menossi(4) on optimization of radiation in the transport of radioisotopes. In the study, approximately 7300 shipments per year of radioisotopes (principally Mo/Tc-99m generators and I-131 compounds); in six types of containers; in special vehicles, commercial planes and long-distance buses; transported throughout Argentina were considered. A cost-benefit analysis, using a value of α = US$ 10,000 showed that increased shielding on packages would be required to obtain an optimized situation. Additional shield thickness of from 0.9 to 1.5 cm of lead with 7% antimony could be justified, reducing the radiation levels 1 m from the package surface from approximately 25 μSv/h to 5 μSv/h for the transport of Mo/Tc-99m and to 2.5 μSv/h for that of I-131. The paper concludes by stating:

> "The values obtained for Argentina cannot be easily extrapolated internationally due to the fact that protection costs and detriment vary from one country to another. However, the cost of protection, X, is highly affected by the cost of the lead used as a shield. Since the cost of lead follows the international metal prices, substantial variations should not be expected among the various countries. On the other hand, the value of α (US$ 10,000/man Sv) adopted by the Argentine authority might be too high for its international acceptance. If a value liable to be more easily acceptable internationally were adopted, such as US$ 5,000/man Sv, the optimized level would remain in about 10 μSv/h at 1 m from the packaging."

Ringot provides useful information in his paper(5) on radiation exposure of transport personnel. These data, which are summarized in Annex IV, provide potential input for optimization studies.

V.3 Examples involving accident situations and risk assessment

Hubert and Pages[6] in their paper on optimization in transport describe the stages involved in their risk assessment as follows:

"The first step includes a description of the logistics of the transportation (quantities, number of shipments, modes, shipping routes), the description of the reference shipment (type of vehicle, type of package, amount shipped, safety devices, etc.).

"The analysis of the shipped material also takes place at this step. It involves the description of its physical and chemical properties, and of the nature of the hazards associated with the loss of the integrity of the package. The hazard can pertain to chemical or radiological toxicity or both. A release can lead to acute or delayed effects such as latent cancer fatalities and genetic effects. In the case of a radioactive material that is non-dispersible, one must consider the external irradiation due to the loss of shielding. In the case of an atmospheric release of dispersible material several pathways will have to be modelled: external irradiation from ground deposits and cloud, internal contamination through inhalation or ingestion of contaminated food. In some cases the risk of criticality should also be considered. All these cases involve quite different time scales and geographic areas. The preliminary analysis performed at this step often allows one to neglect some aspects of the risk. When performing an ALARA analysis, the modelling should be performed with special regards to the alternative safety options at hand in the optimization process. If there is no alternative the model can be simple, if there is one then an appropriate parameter must be present to take it into account. This attitude is often disagreed with on the ground that important parameters are neglected whereas some others of minor importance are taken into account. But that inconsistency disappears when optimization analyses are performed, for the models are used in a comparative manner and not for absolute assessments. At least the general environment must be detailed, that is the actual traffic conditions, the demographic parameters and the weather condition probabilities along the selected routes.

"The second step aims to describe the accident environment - with a view to enable assessing probabilities of events and eventually of the various accident scenarios. At the end of this step the different thermal and mechanical loads which can be applied to the package must have been identified, and the probability distribution of their values estimated.

"In the third step, the package behaviour under the accidental stresses is examined. The probability of a loss of protection as well as the magnitude of a release are associated to the intensity of the loads that can be encountered.

"The last step leads to the assessment of health consequences, with the use of transfer models and demographical parameters. The assessment is generally performed for a first reference option. Then risk is assessed for the other alternatives in order to quantify their effectiveness. Altogether with the assessment of the cost, an ALARA optimization can be done with these data."

The point is made that such probabilistic risk assessments for some systems can be very complex but others may be quite simple.

Other papers concerned with accident conditions include "Cost effectiveness of safety measures applying to hexafluoride transport in France"(7) and a study concerned with transport through the Mont Blanc Tunnel(8). Because of the possible nonavailability of Reference 8, an abstract of this work follows:

"Modifying the regulation for small radioactive package transit through the Mont Blanc Tunnel. An assessment of the health and economic impact."

"The Mont Blanc Tunnel is a 12 km long tunnel, under the highest mountain in Europe, and is one of the most important routes between France and Italy. Hazardous materials are subjected there to much more stringent regulations than is required on plain highways by international regulatory convention (ADR or IAEA). Presently the transportation of small amount of dispersable radioactive material (i.e. whose transportation is allowed in "Type A" packages under a given threshold in activity) is permitted for a truck content which is only one third of the activity limit - A_2 - that is applicable to a Type A package. This probabilistic study aims to assess the implications of a move towards the application of the ADR convention.

"The implications of an accident under the tunnel have first been investigated. Health consequences might be linked to the traffic accident itself or to the release of radioactive materials. In the latter case immediate deaths and late effects of low doses (delayed causes and genetic effects) must be distinguished. There are also three kinds of direct economical impacts: the damage to the tunnel and vehicles, the cost of traffic interruption, and the cost of decontamination.

"Some of these impacts would increase with a change in regulation, but others would decrease and still others would remain unchanged. Allowing for example three times more activity in a vehicle means that the number of shipments is divided by three, and so is the number of accidents. Thus the traffic victims and the damage to the tunnel and vehicles would decrease by a factor of three. A preliminary analysis showed that the cost of decontamination and traffic interruption would also decrease, since these are less than proportional to transported activity. The delayed effects of radiation being linear with the dose, and the dose being linear to the activity, would not be modified. On the other hand, immediate effects are most likely to increase.

"The decisional process implies knowing the answers to these two questions. Are the new levels of risk acceptable? Is the measure cost effective?

"A conservative approach has been used to answer the first question, with the transport of a total immediate release by air along the tunnel being assessed using a compartment model, and a puff model in the first compartment. The accident individual dose to the public would be about $6\ 10^{-2}$Sv in the most contaminated part of the tunnel, instead of 2 in the case of the present activity limit. These figures illustrate that the conditions of dispersion within the tunnel are quite close to the assumed hypothesis for deriving this A_2 limit in the IAEA guidelines.

"Immediate death can follow exposure in a tiny volume downwind the source. In the most severe compartment lethality can be observed up to 2.5 m downwind, but within a 10 cm radius. Such a volume is about 5 times bigger ($3^{3/2}$) than it would be for the 1/3 A_2 limit, and so is the probability to encounter such effects for a given traffic. It is very likely that the "acceptability" of the risk would be the same in the two cases.

"A risk benefit analysis is then conducted. But as all nonradiological risks are decreasing and as they are more important than radiological risk, the results are that such an option both saves money and reduces risk. The point is rather to study the transfer from nonradiological to radiological risk. Presently a test programme on the behaviour under accidental stresses of these packages is carried out in the CEA to improve the accuracy of this probabilistic risk assessment and future safety studies."

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