IAEA-TECDOC-767

Safety indicators in different time frames for the safety assessment of underground radioactive waste repositories

First report of the INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal

INTERNATIONAL ATOMIC ENERGY AGENCY

The IAEA does not normally maintain stocks of reports in this series. However, microfiche copies of these reports can be obtained from

INIS Clearinghouse
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

Orders should be accompanied by prepayment of Austrian Schillings 100,— in the form of a cheque or in the form of IAEA microfiche service coupons which may be ordered separately from the INIS Clearinghouse.

The originating Section of this document in the IAEA was:

Waste Management Section
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

SAFETY INDICATORS IN DIFFERENT TIME FRAMES
. FOR THE SAFETY ASSESSMENT OF
UNDERGROUND RADIOACTIVE WASTE REPOSITORIES

IAEA, VIENNA, 1994
IAEA-TECDOC-767
ISSN 1011-4289

Printed by the IAEA in Austria
October 1994

FOREWORD

Plans for disposing of radioactive wastes have raised a number of unique and mostly philosophical problems, mainly due to the very long time-scales which have to be considered. While there is general agreement on disposal concepts and on many aspects of a safety philosophy, consensus on a number of issues remains to be achieved.

To assist in promoting discussion amongst international experts and in developing consensus, the IAEA established a subgroup under the International Radioactive Waste Management Advisory Committee (INWAC). The subgroup was established in 1991 and is called the "INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal".

The subgroup is intended to provide an open forum for:

(1) the discussion and resolution of contentious issues, especially those with an international component, in the area of waste disposal safety principles and criteria,

(2) the review and analysis of new ideas and concepts in the subject area,

(3) establishing areas of consensus,

(4) the consideration of issues related to safety principles and criteria in the IAEA's Radioactive Waste Safety Standards (RADWASS) programme,

(5) the exchange of information on national safety criteria and policies for radioactive waste disposal.

The first report of the subgroup deals with the problem of establishing appropriate indicators of safety for underground radioactive waste repositories in the presence of increasing uncertainty in the results of the safety assessments with time after closure of the repository. It discusses the different types of safety indicator which could be used and the nature of the safety case which can be expected at different times in the future.

EDITORIAL NOTE

CONTENTS

5/6

1. INTRODUCTION

Principles and criteria for the disposal of long lived radioactive waste involve issues which go beyond those normally considered in the basic system of radiation protection. One important principle which seems to have broad acceptance is that a similar level of protection should be provided for future generations as that provided for the current generation. There are difficulties in showing compliance with safety criteria over long time-scales because of the increase with time of the uncertainty associated with the results of predictive models. On the other hand, the radiotoxicity of the wastes decreases with time due to radioactive decay. These contrary trends suggest that the meaningfulness of and the need for detailed quantitative assessments become less and less the further into the future the assessment is carried. It is generally considered appropriate, however, to continue assessments sufficiently far into the future to ensure that any peak in potential impact of the disposal facility has been taken into account. The only adjustment to this principle might arise if qualitative studies were to show the peak impact to be so low as to be considered trivial.

The general principles for protecting individuals from the harmful effects of ionizing radiation have been developed by international organizations over many years. They are based on the tenet that any dose of radiation could cause harm; they aim to limit the likelihood of this harm occurring to acceptable levels. Thus, as discussed in the Annex, the dose limit sets a bound on the level of risk to an individual's health from all controlled sources of ionizing radiation. Similarly, dose constraints limit exposures from a single source. Safety criteria based on radiation risk and dose limitation are commonly accepted as the principal basis for judging the acceptability of radioactive waste repositories. However, the long time-scales of interest mean that risks or doses to future individuals cannot be predicted with any certainty as they depend, amongst other things, on assumptions made about the integrity of the waste matrix, the man-made barriers, the geology, the dispersion of groundwater, etc. and future biospheric conditions and human lifestyles. This has led the international community to consider the "assessed long term radiological consequences of disposal systems" (expressed in terms of dose and risk) only as "indicators of safety that can be compared with criteria" [1]. For these reasons, it has been proposed that dose and risk criteria should be supplemented with other types of safety indicator which rely less on assumptions about future conditions.

This document discusses various safety indicators and their applicability in the context of the future time-scales which have to be considered in safety assessments of deep geologic repositories.

Since the terms quantitative and qualitative (assessments) are used throughout this text, it is appropriate for reasons of clarity to provide the following definitions:

quantitative assessments are based on numerical estimates of consequences (e.g. risk or dose) and the assessment is made against numerical criteria.

qualitative assessments are based on estimates of hazard potential which are not exact or absolute and the assessment is made against criteria which may not be numerically defined. Examples of such criteria are the convenient reference values provided by levels of radionuclides in the natural environment.

2. SAFETY INDICATORS

2.1. INTRODUCTION

The purpose of this section is to discuss the role and utility of various types of safety indicator over a range of time-scales. The indicators of particular interest are those which are useful over longer time-scales (10^2–10^6 years).

The overall objective of any safety evaluation of a repository must be to estimate the associated impact on human health and the environment. In order to achieve this, mathematical models are used to simulate any migration of radionuclides from the waste, through the engineered barriers and the geosphere, to the biosphere and the human environment. These processes are illustrated in Fig. 1. Uncertainties increase as more processes are taken into account and the greatest uncertainties will, therefore, surround the estimates of health impact. It is possible to take intermediate quantities such as predicted flux from geosphere to biosphere or environmental concentration and use these to provide a

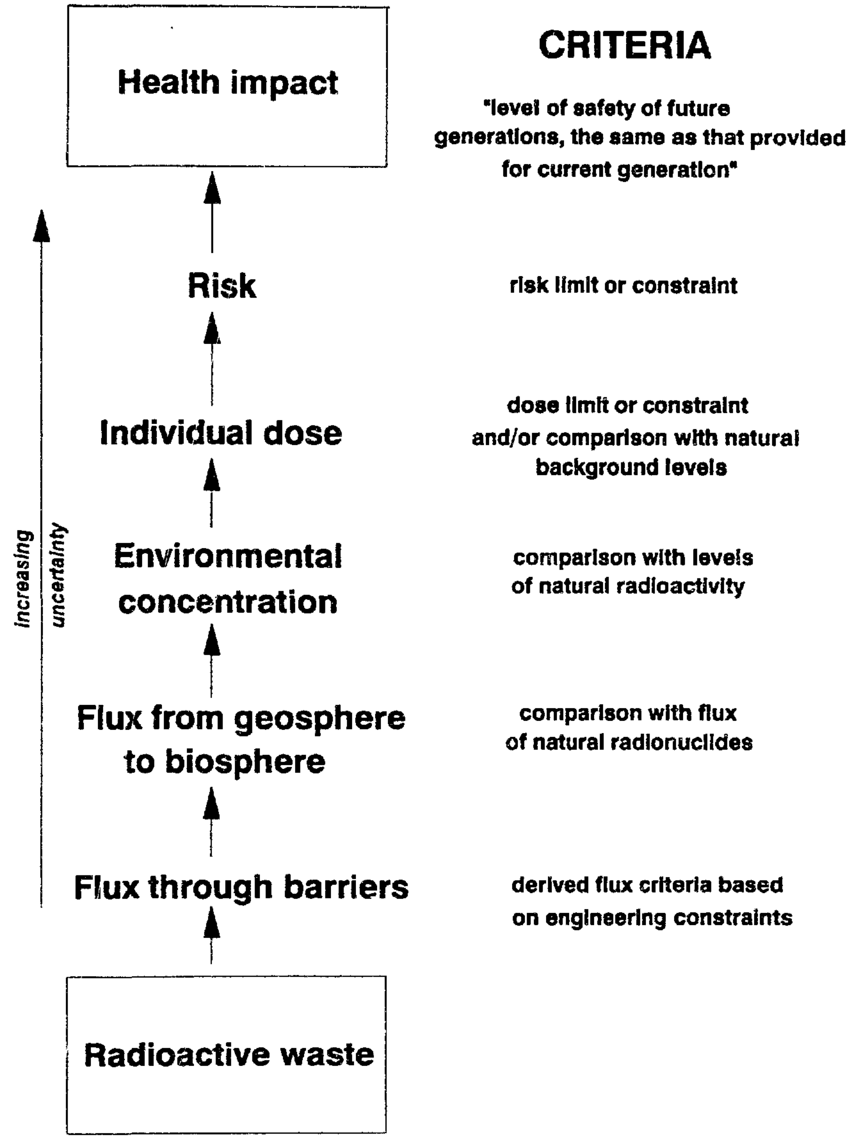

FIG. 1. Hierarchy of safety indicators.

measure of the safety of the repository. Such indicators while also subject to uncertainty are only useful if they can be compared to some known data, eg., data from natural processes.

It is generally assumed that adequate protection of the environment can be inferred from the continuing well-being of humans [2, 3], and thus the indicators risk and dose in Fig. 1 could also serve as environmental indicators. However, environmental concentrations and fluxes may be more immediate indicators of environmental impact.

Indicators can serve a variety of purposes. For example they can provide information necessary to:

- provide a basis for comparison of various repository options;
- make regulatory decisions on the safety and licensability of a repository by showing compliance with criteria;
- make engineering decisions on the siting, design and construction of the facility;
- generate confidence in the ability to conduct safety assessments and in the safe performance of the facility;
- provide context, perspective and a basis for comparison of the facility performance with other similar societal activities;
- aid in communicating with decision makers and non-technical audiences.

Some indicators are more suited to the short time scale and others to the long time scale. In most cases more than one will be needed to provide either sufficient information or sufficient confidence to make a decision.

2.2. DESIRABLE CHARACTERISTICS OF SAFETY INDICATORS

Indicators can vary widely in their characteristics and their utility. The following characteristics are suggested as a basis for judging the quality of an indicator:

reliable – they should be based on well established principles and be applicable over a wide range of situations;

relevant – they should relate to the important safety and environmental features of the repository;

simple – they should be simple and not overly complex otherwise they will be less used and take more time and effort to apply. Simple indicators can facilitate communication;

direct – the indicators should be as closely linked to some primary system property as possible and should involve the minimum of computation for translating available information to the format of the indicator;

understandable – users should know exactly what the indicators represent and how to determine its value. This links with the needs of simplicity and directness;

practical – the data and the tools or models needed should be available and well based.

It is recognized that no one indicator can be expected to meet all of these desirable characteristics. However, as a guiding rule, those with a large number of deficiencies in relation to the above list should be avoided. It is also recognized that if a reasonably complete understanding of a system is needed, several independent but complementary indicators may be needed. Some caution, however, has to be exercised so that the total system of indicators does not become overly complex in the hope of achieving a complete performance measure. A balance between completeness and simplicity is needed.

2.3. TYPES OF SAFETY INDICATOR

2.3.1. Radiological safety indicators

The purpose of radioactive waste repositories is to isolate wastes from the biosphere. It is generally accepted that isolation and containment cannot be guaranteed and that in geological time frames, sooner or later, a fraction of the radioactive inventory may be released from the repository, migrate through the geosphere and eventually reach the biosphere, even though it may take thousands or even millions of years if it occurs at all. A performance assessment of a repository involves the application of mathematical models that simulate the physical and chemical processes which will occur in the various compartments: repository, geosphere and biosphere. The end result is usually an estimate of the dose received by human beings that are supposed to be at some specific location and to be exposed, in some way, to the radionuclides released from the repository. The dose can be transformed to a corresponding risk level by direct application of the ICRP risk factor and by taking account of the likelihood of exposure.

In the present context, the use of dose or risk as safety indicators has one main disadvantage which is concerned with the uncertainty surrounding their estimation. This is largely associated with the uncertainty regarding the future state of the biosphere (human beings and foodchains) and of conditions in the near-surface zone. Furthermore, this uncertainty will increase with the time period under consideration. At the same time, it is noted that there is also considerable uncertainty associated with predicting radionuclide transfer through the multi-barrier system and the geosphere and that this uncertainty afflicts almost all safety indicators.

In the following sections, the applicability of the risk and dose concepts to long term safety assessment is briefly discussed (it is taken up in more detail in the Annex).

2.3.1.1. Risk

Several countries have decided to use the individual risk of health effects (mainly radiation induced cancer) as the primary indicator of repository performance. A typical application of risk[1] for limiting the impact of a repository is to establish a numerical risk limit applicable to any individual affected by the repository at some time in the future.

The use of risk as a safety indicator of radioactive waste disposal has both advantages and disadvantages. One advantage is the general applicability of the indicator. Risk is associated with all human activities and the risk from a particular cause can be compared

[1]Risk in this context is normally defined as the product of the probability of exposure to a particular dose and the probability of a health effect arising from that dose.

readily with risks from any other cause. The use of the same safety indicator for all human activities allows ready comparison and may be of assistance in the rationalization of societal decisions, for example in the area of resource allocation. An additional advantage of using risk as an indicator is that a single parameter can contain the results of all types of scenario. It can encompass the extremes of gradual or normal evolution scenarios that have a probability close to one but low consequences and disruptive scenarios which have a low probability of occurrence but may have comparatively high consequences. This is discussed in more detail in the Annex.

In addition to the general problem of uncertainty in the long term mentioned in the introduction to this section, another disadvantage of using risk as a safety indicator for radioactive waste repositories is that risk values are not necessarily useful in communicating with the public and in illustrating the safety of a particular activity. Risk is a difficult concept to explain to people and, for example, there is a tendency for much more attention to be paid to the consequences of an event than to the probability with which it is expected to occur.

2.3.1.2. Dose

Radiation dose is a measure of the energy deposited by radiation. When appropriately weighted for radiation type and human tissue sensitivity (effective dose) it can be directly correlated with the probability that harm will be caused.

The use of dose as a safety indicator for repository performance is supported by tradition and national legislation. Since the early days of radiation protection, control has been based on limiting doses to individuals. Dose is the common basis for expressing the impact of radiological events and is used as a measure of the important reference quantity — natural background radiation.

Individual dose rather than collective or population dose is used in most countries as the main safety indicator for repository performance, since the size and distribution of future populations in the vicinity of a repository cannot be known with any useful precision. However, the size of the exposed group is a factor to be considered in assessing the significance of an event. Thus, a drilling intrusion scenario that exposes a necessarily small drilling crew may be weighted differently from a scenario leading to radionuclides entering the food chain that can result in ingestion by a large group of people taking into account not only individual doses but the number of people exposed. This weighting of doses on the basis of sizes of potentially exposed groups has been proposed in some countries, but not in quantitative terms.

Individual dose as a safety indicator for geological repositories has the considerable advantage of being a familiar measure which can be compared with other types of radiation exposure and with natural radiation background. Thus, although the doses from gradual release scenarios are being predicted to hypothetical critical groups in the far future, the element of familiarity is still present, and the usual comparisons with dose limits and natural background levels can be made.

The use of dose as an indicator for probabilistic or disruptive scenarios presents problems (see Annex). In other areas of radiation protection where dose is used as a safety indicator, the radiation exposures are expected to occur with a high probability and the principles of dose limitation can be applied. However, in the case of radioactive waste repositories where, in the event of disruptive scenarios, doses could be received but with a low probability, dose limits cannot be directly applied. In some countries a judgement is made as to which scenarios are sufficiently improbable to be neglected and the remainder are conservatively treated just as if the probability of occurrence is unity. In this way, dose can be used as a universal safety indicator for waste repositories. Alternative approaches are to apply a risk indicator as described in the previous section in the assessment of probabilistic scenarios and a dose indicator for the normal, gradual release scenarios (hybrid dose/risk system) or to use a risk indicator as the safety criterion for all scenarios (see Annex).

2.3.2. Other safety indicators

The movement of radionuclides out of a repository and into the human environment is governed by transport processes within the engineered and natural barriers. There is a strong interrelation between the characteristics of the system; ineffective barriers and a large release rate may cause high fluxes of activity into the biosphere causing high concentrations in the surface environment. Thus characteristics of this kind may be used as additional indicators for safety as shown in Fig. 1. In this section, concentrations, fluxes through barriers and the biosphere, radiotoxicity and time will be discussed as indicators.

The most relevant indicators are those which can be compared with data from natural analogue studies. This is because relevant predictions for the future are made by extrapolating data and models based on evidence of the dynamic evolution of the geological system.

It is noted that dose and risk are already established as appropriate and well understood safety indicators for use in this context. The other safety indicators discussed in the following sections do not yet enjoy the same widespread recognition and more experience needs to be gained in their use and application.

2.3.2.1. Flux

Flux or flow is a measure of dynamic performance as it describes the rate of movement across interfaces or barriers in a system. It can be used as a direct measure of the containment provided by various barriers.

(a) Fluxes through barriers

Fluxes within the multibarrier system of a repository have been used for establishing indicators of barrier performance and for setting corresponding criteria.

Indicators of this kind are useful tools for the implementor in the iterative process of site investigation and design of a repository, and in supporting research and development programmes; they can be a base for making prioritizations and allocating resources. Care should be taken, however, that they do not distract the focus of interest from overall safety objectives to single components in the barrier system. Furthermore it is difficult to link fluxes through engineered barriers directly to safety.

The fluxes may be based on total activity, or activity of critical nuclides, and they may be given as fractional release rates from the repository containment. In the latter case, the future time period over which the calculation of the total activity has to be performed must be specified.

Fluxes are useful indicators to facilitate understanding of the natural processes which existed in the past at a repository site and which may contribute to the long term isolation of the waste.

(b) Fluxes in the biosphere

The impact of radionuclides on any given biosystem is governed by, amongst other things, the flow of activity into the system. The radiological consequences depend on the resulting levels of environmental contamination and the potential for human exposure in the environment. As already discussed, there are great uncertainties in the assessment of these factors in the very long term. The use of flow, or flux, of radionuclides may circumvent some of these difficulties by providing a comparison with the flux of natural radionuclides into and through the biosphere.

The concentration of natural radionuclides in specific environmental compartments is a result of the dynamics of natural radionuclide transport in the environment. The natural cycles of matter provide, by processes like erosion, dissolution in water, water flow, sedimentation, resuspension and transport by wind, a continuous flow of natural radionuclides from land into the sea, through rivers and lakes. Inevitably, some exposure of humans results from that flow. By comparing the flow of radionuclides from a repository with the flow of natural radionuclides averaged over a wide area and over long time-scales, there is the possibility of obtaining a relative measure of radiological significance of the flow of radionuclides from the repository.

The use of flux to large receptors, such as seas and oceans, as a safety indicator makes the calculation less dependent on assumptions about the environment, pathways, intakes and radiosensitivity (for comparable nuclides). Any property of any part of the chain between source and man will influence the doses from the repository and from the reference flows in approximately the same way [4]. Such fluxes are more appropriate as indicators of the impact on larger populations or globally since the properties of larger receptors are not as variable as those of lakes and rivers in the long term.

However, this safety indicator does not provide a measure of the safety of individuals at the local scale, i.e. those living in the vicinity of the repository, and therefore it needs to be used together with another more localized safety indicator.

Before applying flux as an indicator, it has to be ensured that the natural flux, based on measurements, is evaluated and described on the same basis as the calculated flux from the repository. For example, the natural flux might be dominated by transport of mineral particles, which implies that the radionuclides are present in a form not easily absorbed by biota. On the other hand, in calculations of flux from a repository, it is usually assumed that the nuclides are in solution.

The flux as an indicator of the impact on the biosphere has the advantage that it is given directly as the output from transport calculations for the far-field in safety assessments. Some care must be exercised in defining the location of this flux, however. Usually the flux is assumed to be located at the relevant boundary of the rock formation, or more generally at the boundary between the far field and the biosphere or the accessible environment.

To date, biospheric flux has found only limited application as an indicator [4]. A number of problems with the indicator require further attention:

(a) a satisfactory means of quantification of the indicator needs to be devised which is independent of other indicators, e.g., dose and risk;
(b) a method has to be established for dealing with non-naturally occurring radionuclides in the repository for which no natural analogues exist;
(c) in view of the local variability of natural fluxes, a means for obtaining an averaged representative flux for comparison with calculated fluxes from the repository needs to be developed.

2.3.2.2. Time

Time, or rate of change, can be an important and useful indicator of the overall potential of a repository or its individual components to isolate and contain hazardous materials. For example, time can be used as a direct indicator:

- to show how a natural or engineered barrier performs by observing or describing how long it takes for an isotope to pass through it or to describe the time needed to transmit a given quantity of that element;

- of the relative rate of movement of different elements and thus the capacity of the barrier to retard movement beyond that determined by the bulk ground water flow;

- of the isolation potential of the natural system by using the age of the deep groundwater as an indication of the degree of mixing between deep and surface waters;

- to describe the rate of change of important parameters of the natural system (pH, Eh, hydraulic gradients, etc.) or to describe the natural evolution of minerals in the repository (bentonite to illite clay forms).

2.3.2.3. Environmental concentration

The concentration of a contaminant at a specific time and location can provide an indirect indication of the potential effect on humans and their environment. By making some assumptions about the surface hydrosphere, exposure pathways and the habits of a human population group, an estimate of dose or risk can be made on the basis of the information on concentration. However, the uncertainties which are introduced by making these assumptions can be avoided by using concentration itself as the safety indicator.

If the concentration in the outflow from the geosphere is taken as the indicator, only dilution in the geosphere has to be taken into account. Similarly, the use of concentration as an indicator for evaluating the consequences of intrusion by drilling wells, etc., avoids some of the uncertainties involved in dose estimation.

It is relatively easy to establish a reference for the assessment of concentrations by using the natural radionuclides which exist in the environment, although some "radiological equivalence scheme" may have to be developed for the non-naturally occurring radionuclides in the repository. One suggested approach is to assume that the artificial radionuclides are of comparable radiotoxicity to the natural alpha emitters. Then the total activity concentration could be compared with that due to natural alpha activity. Other possibilities include comparisons based upon radiotoxicity, e.g., by dividing the concentrations in Bq L^{-1} by the respective values of annual limit of intake (ALI) as specified by the ICRP [5].

The comparison with natural concentrations and fluxes may be questionable for some geological formations, notably salt, that contain only small amounts of natural activity. As a consequence, the comparison of environmental concentrations due to the presence of a repository may well indicate a considerable increase above the natural level of that locality. In these circumstances, the argument would have to be made that an appropriate comparison would be with the average natural concentration in a larger region.

2.3.2.4. Radiotoxicity indices

Indices which use the inherent hazard presented by radioactive waste as a safety measure have been widely used. In particular, they have been used to indicate the time needed before the hazard presented by the waste declines to that of natural uranium ore.

Several different indicators of radiotoxicity have been used based on various radiological parameters, such as total activity, specific activity, activity per unit volume, the number of annual limits of intake (ALIs) by ingestion or by inhalation contained in the wastes, etc. The index is often rendered dimensionless by direct comparison with a reference material — again the comparisons vary. Comparisons have been made between the activity in a certain amount of waste and that in the mass of uranium ore used to produce it [6], between the activity per unit volumes of the ore and waste, between the activity per unit volume of the ore and of the average activity per unit volume of a geological waste repository (allowing for the overall area over which the waste is emplaced) [7]. Another comparison involves the activity in a certain amount of waste, and the activity of the uranium destroyed by fission to produce it [8]. The radiotoxicity of radioactive waste has also been compared to the toxicity of solid residues of coal burning and other non radiological hazards [9, 10].

In all of these comparisons it is of interest to observe the time in the future when the "toxicity" of the radioactive waste becomes equal to that of the natural material — the crossover time. Though the estimated crossover times in the different studies vary by several orders of magnitude, they are within the range covered by the isolation potential of repositories in deep geological formations. Depending on the assumptions and terms of comparison, most of the radiotoxicity curves found in the literature show crossover times from a few thousand to a few hundred thousand years.

Radiotoxicity indices are useful in putting the potential hazards of radioactive waste disposal into perspective; they show the decline with time of the potential hazard presented by radioactive wastes and, specifically, the time at which the potential hazard becomes comparable with natural materials, such as uranium ore. Thus, they are qualitative indicators of the time-scales of interest for safety analysis.

There are limitations to their usefulness, however, since they only indicate hazard potential and do not represent the actual hazard presented by wastes in a repository. For such an evaluation there is no substitute for a formal safety analysis which evaluates the events which must occur before exposure of humans can happen. The analysis must take account of the effects of man-made and natural barriers, and geospheric biospheric transport processes, and pathways to man.

2.4. SUMMARY

A summary of the advantages and disadvantages of the various safety indicators discussed in this section is provided in Table I.

TABLE I. A COMPARISON OF THE SAFETY INDICATORS

Indicator	Advantages	Disadvantages
	Humans	
(1) Risk	Direct indicator of impact on humans	Possible communication problems
	Integrates all exposure routes to humans	Problem in estimating probability
	Can take likelihood of exposure into account	problems of applicability in far future
	Enables direct comparison with other hazards	Calculational complexity
(2) Dose	Well established and understood	Does not take likelihood of exposure into account
	Direct indicator of impact on humans	Problems of applicability in far future
	Integrates all exposure routes to humans	
	Environment	
(3) Environmental concentration	Conceptually simple	No direct natural comparators for artificial nuclides
	Independent of human status	Problems in defining a generic reference level
	Measure of local environmental impact	
(4) Biospheric flux	Relatively independent of local biosphere and human changes	Conceptually difficult
	Measures regional and global environmental impacts	Problems in defining generic reference level
		No direct natural comparators for artificial nuclides
		Not a local safety indicator
(5) Flux through barriers	Direct indicator of barrier performance	May not be directly related to safety
		Could divert attention from overall safety objectives
(6) Time	Easy to understand	May not be directly related to safety
	Direct indicator of barrier performance	
	Waste	
(7) Radiotoxicity	Conceptually simple	Incomplete and sensitive to assumptions
	Indicator of time periods of concern	

3. USE OF SAFETY INDICATORS IN RELATION TO TIME FRAMES

3.1. INTRODUCTION

The ability to estimate values for the various indicators identified in Section 2 varies in time. The uncertainty increases continuously with time but it is convenient to use a few specific time intervals as a framework for discussing how the utility of each indicator varies in time. The time frames to be considered are:

(a) closure - 10^4 years;
(b) 10^4 - 10^6 years;
(c) beyond 10^6 years.

Again it is important to emphasize that the demarcation times of 10^4 and 10^6 years are indicative only and should not be interpreted as being sharply defined.

The numerical values of indicators for a nuclear waste disposal facility are often estimated by means of mathematical models. The reliability of these models depends, inter alia, upon the amount and quality of the information available and it will decrease with time. Therefore, for long term assessments, the confidence in the results also decreases.

It is clear that assessments which extend into the very far future, beyond times of the order of 10^6 years, are characterized by very large uncertainties, and even those with time-scales of 10^4 or 10^5 years will be subject to considerable uncertainty.

One suggested approach to the problems of safety assessment over very long time-scales has been to introduce a regulatory "cut-off" time beyond which safety assessments would not be required for licensing purposes. However, such a cut-off could lead to underestimation of the hazard to the public and would contradict the principle that radiological protection should be independent of time. Therefore such a cut-off in assessments would not be appropriate at a time when doses or other safety indicators are still rising. In this respect, for a deep repository, the time before activity could first reach the biosphere may be considerably greater than 10^4 years.

On the other hand, the nature of the safety assessments needed at times far in the future is different from those in the years soon after repository closure. The change may be characterized by a gradual shift in time from quantitative to qualitative assessments. In particular, detailed assumptions about the near-surface zone, the biosphere and human behaviour in the far future are unlikely to be justified. For long time-scales, effort would be better concentrated on the reliable assessment of radionuclide transfer to the biosphere.

In the following sections, a generic discussion is presented on the possibilities and limitations for evaluating the long term safety of final disposal sites through the use of various indicators. However, final disposal sites must be evaluated on the basis of site specific studies and safety assessments which allow for the unique characteristics of the wastes and the site to be fully considered.

As a basic principle, predictions for the future are made by extrapolating data and models based on evidence of the dynamic evolution of the geological and other systems in the past. There is an increasing use of natural analogues to support assessment methods, to provide reference values for comparison with calculated indicator values and to provide perspective. In recent initiatives, use is being made of information, e.g., from the field of paleohydrology, to help understand how natural geological systems evolve with time. This understanding may help to support decisions on the long term safety and performance of geological repositories.

3.2. FROM THE TIME OF FACILITY CLOSURE UP TO ABOUT 10^4 YEARS

Information about the repository and possible institutional control over the site is often assumed to be retained for at least several hundreds of years after the facility is sealed. The assumption is difficult to demonstrate but it is highly desirable that, as a minimum, information about the location of the repository is retained. At the other extreme of this range, significant natural changes in the deep geological systems are unlikely on the time scale of 10^4 years provided that the sites are located in tectonically stable areas.

The major changes in the climate which are of potential importance are those that may arise from possible greenhouse effects, which could result in some changes to the landscape (drying up or overflowing of rivers and lakes, moderate sea level-changes and coastal erosion). However, in general, the biosphere may be assumed to remain comparable to present day conditions, that is, in the form in which it has been shaped by man since the introduction of agriculture 10^4 years ago. It does not seem unreasonable to suppose that there will be an interest in maintaining conditions close to the present ones, i.e. favourable to agriculture.

For the purposes of assessing the consequences of future human actions, for example, intrusion into a disposal site, the future level of technology should be assumed to be at least equivalent to that existing at present. A lower level of technology would make it less likely that intrusion could be technically achieved. On the other hand, an improved technology supposes an increased knowledge, retention of records and an awareness of the risks of such repositories. Deliberate human intrusion (i.e. with knowledge of the location and nature of the waste) is believed to be beyond the scope of what should be considered in a safety assessment. It is recognized, however, that unintentional or accidental intrusion could take place and that its likelihood should be reduced as much as possible by selecting appropriate sites and repository designs.

While it is recognized that considerable uncertainty can exist during this time period, it is still reasonable to attempt to make quantitative estimates of the indicators to be used. The calculations should take into account the range of biosphere conditions. It should be emphasized that these estimates are not seen to be accurate predictions of future repository performance but rather as providing general indications of that performance and of the overall safety of a repository. During this period the radiological safety indicators will be of primary importance — with the other indicators providing additional support, context and perspective. They can also provide an indication of possible impacts on the environment itself. The use of reference biospheres[2] is an emerging concept and its use in this time frame is likely to increase since it can eliminate much speculation on the exact nature of future environments.

[2]Reference biosphere: This concept has been introduced as a standardized approach to biosphere modelling in the context of the safety assessment of radioactive waste repositories mainly because the future biosphere associated with a given repository cannot be known. The advantages of the concept are that it avoids speculative discussion of the future by providing a simple, robust and defensible approach to representing transfer through the biosphere to humans at future times. Also, the adoption of a reference biosphere could make the comparison of different disposal options easier by allowing focus to be placed on geological transfer issues.

3.3. THE PERIOD FROM ABOUT 10^4 UP TO ABOUT 10^6 YEARS

In this time frame, long term natural changes in climate will occur. The climatic system may recover from any possible greenhouse gas effects at the beginning of this period, and glacial/interglacial cycling may take place. The sea level could drop by up to 140 m during glacial periods, and glacial or periglacial conditions will occur in the high latitudes for a substantial portion of the time. Low latitudes are likely to be affected to a lesser extent but changes due to alternate pluvial and dry periods may occur. The impacts of these phenomena can be evaluated by means of simple generic sensitivity and bounding studies and by the use of reference biospheres which encompass the range of the viable biospheres which currently exist.

Generally, major tectonic changes are not expected during this time frame, but local readjustments, such as isostatic rebound, are possible. Thus major changes in the way contaminants are transported from deep geological repositories are unlikely. This longer term stability is offset to some extent by the uncertainty in estimating geosphere transport characteristics.

While it may be possible to make general predictions about geological conditions, the range of possible biospheric conditions and human behaviour is too wide to allow reliable modelling. The emphasis of assessment should therefore be changed so that the calculations relating to the near-surface zone and human activity are simplified by assuming present day communities under present conditions. Such calculations can therefore only be viewed as illustrative and the 'doses' as indicative. The use of reference biospheres will likely become a principal tool in this time frame. At the same time other safety indicators, requiring less information about near surface conditions, the biosphere and human behaviour, will play an increasing role.

Studies on toxicity indices suggest that, in this time frame, the potential hazard associated with radioactive waste falls close to or below that of the naturally occurring ore from which it is derived. Therefore it may be appropriate to use quantitative and qualitative assessments based on comparisons with natural radioactivity and naturally occurring toxic substances.

3.4. THE PERIOD BEYOND ONE MILLION YEARS

The arguments given in the previous two sections become increasingly more applicable as the time extends beyond 10^6 years. One million years is the approximate time since the emergence of homo sapiens. Furthermore, at periods of approximately 10^7 years, even geological predictions have little scientific basis since unpredictable large scale changes take place, e.g., mountain building, continental drift, and massive erosion. The toxicity studies (Section 2.3.2.4) suggest that the waste hazard in this period could be considered equivalent to naturally occurring materials since it is primarily due to the natural isotopes of the U and Th chains. From these arguments it can be concluded that little credibility can be attached to assessments beyond 10^6 years. Even qualitative assessments will contribute little to the decision making process.

4. SUMMARY ON SAFETY INDICATORS AND TIME-SCALES

1. The assessed long term consequences of disposal systems in terms of risk and dose can only be considered as indicators of safety.

2. The long term safety case can be made most effectively by the combined use of several safety indicators, such as risk, dose, environmental concentration, biospheric flux, flux through barriers and time recognising, however, that risk and dose remain the most fundamental of the indicators of safety.

3. Indicators become particularly valuable when they are supported by observations from natural analogues.

4. In the time period up to around 10^4 years after repository closure, the safety case should be based on quantitative safety assessments using dose/risk calculations supported by calculations involving other safety indicators.

5. In the period from around 10^4 years to about 10^6 years after repository closure, the safety case should be based either on quantitative safety assessments or on qualitative assessments using a combination of safety indicators. The emphasis may be expected to shift increasingly towards qualitative assessments as 10^6 years is approached.

6. Beyond about 10^6 years little credibility can be attached to integrated safety assessments.

REFERENCES

[1] NEA/IAEA/CEC, Disposal of Radioactive Waste, Can Long-term Safety be Evaluated? An International Collective Opinion, OECD/NEA, Paris (1991).

[2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Ann. ICRP 21 (1-3), Pergamon Press, Oxford and New York (1991).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards, Technical Reports Series No. 332, IAEA, Vienna (1992).

[4] THE RADIATION PROTECTION AND NUCLEAR SAFETY AUTHORITIES IN DENMARK, FINLAND, ICELAND, NORWAY AND SWEDEN, Disposal of High Level Radioactive Waste, Consideration of some Basic Criteria (1993).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Annual Limits on Intake of Radionuclides by Workers Based on the 1990 Recommendations, Publication 61, Ann. ICRP 21 No. 4, Pergamon Press, Oxford and New York (1991).

[6] COHEN, J.J., DAER, G.R., SMITH, C.F., VOGT, D.K., WOOLFOLK, S.W., "An assessment of issues related to determination of time periods required for isolation of high level waste", Waste Management '89 (Proc. Symp. Tucson, AZ, 1989), Arizona Board of Regents (1989).

[7] HILL, M.D., "The hazard associated with vitrified high level radioactive waste", Radiological Protection Bulletin, UK National Radiological Protection Board **21** Chilton (1977).

[8] GERA, F.,"Geologic predictions and radioactive waste disposal: a time limit for the predictive requirements", Predictive Geology with Emphasis on Nuclear Waste Disposal (DE MARSILY, G., MERRIAM, D. F., Eds), Pergamon Press, Oxford (1981).

[9] EHRLICH, D., ROTHEMEYER, H., STIER-FRIEDLAND, G., THOMAUSKE, B., Langzeitsicherheit von Endlagern, Atomwirtschaft **31** (1986) 231-236.

[10] BROOKINS, D.G., VOGLER, H.A., Playas and naturally poisoned areas of Nevada and Western Utah, University of New Mexico Report to Lawrence Livermore National Laboratory, July 1981.

Annex

DOSE AND RISK AS SAFETY INDICATORS

A-1. INTRODUCTION

In order for nuclear power to be a viable option for generating electricity, it is imperative that ways are found for the safe disposal of radioactive waste. However, long lived radioactive wastes may cause exposures of individuals over many thousands of years into the future. The central ethic for radiological protection in such circumstances is that individuals alive in the future should be protected to the same degree as individuals are today. The problem is how to set radiological protection criteria which ensure this.

The purpose of this Annex is to look at various ways of setting radiological protection criteria appropriate to solid waste disposal, concentrating in particular on setting them in terms of doses or risks; comparing the advantages and disadvantages of each method; and attempting to reach some overall conclusions. The paper only covers the post-closure period of a facility and also only discusses criteria which attempt to limit individual harm — no attempt is made at considering doses or risks to populations: that information is usually required as an input into optimization studies which are the subject of a separate discussion paper. Firstly we will look at the problems involved in setting radiological protection criteria for solid waste disposal and ask the question: why can't you use a system of dose limitation directly?

A-2. THE PROBLEM WITH 'DOSE'

Some radioactive wastes are very long lived and, following disposal, may be released to the human environment, the biosphere, over hundreds of thousands of years. Over such time periods the rate of release to the biosphere cannot be predicted with any certainty, rather it depends upon events and processes which are characterized by probabilities of occurrence (Fig. A-1). Furthermore, the exposure of individuals in the future will depend upon, amongst other things, their habits and the status of the biosphere, both of which are very uncertain. In this situation it is difficult to apply standards which are based solely on dose limitation.

The example of a deep geological repository for high level radioactive wastes serves to illustrate some of the issues. If there were human intrusion into the repository by, say, exploratory drilling and bringing a core to the surface, then it is conceivable that a technician inspecting the core would receive sufficient radiation exposure to cause death within the following few weeks. Clearly, such a dose would be in excess of any dose limit imposed on the repository and, furthermore, the probability of such human intrusion may be said to be very low but it cannot be considered to be zero. This is an extreme example but in most situations it is generally possible to envisage circumstances, even if they are very unlikely ones, which would lead to doses above the dose limit: setting criteria *solely* in terms of dose may lead one to reject many, if not all, disposal options for most categories of waste.

It could be argued by analogy with critical group assessments for current, routine releases that it is only necessary to consider the most likely exposure situation. However, in the case of controlling such current operations, if anything untoward happened to affect exposures then corrective measures could be taken at the source. For solid waste disposals, exposures may arise after the period of institutional control; therefore, no corrective measures can be assumed and in order to adequately protect future individuals, many possible exposure situations may need to be considered.

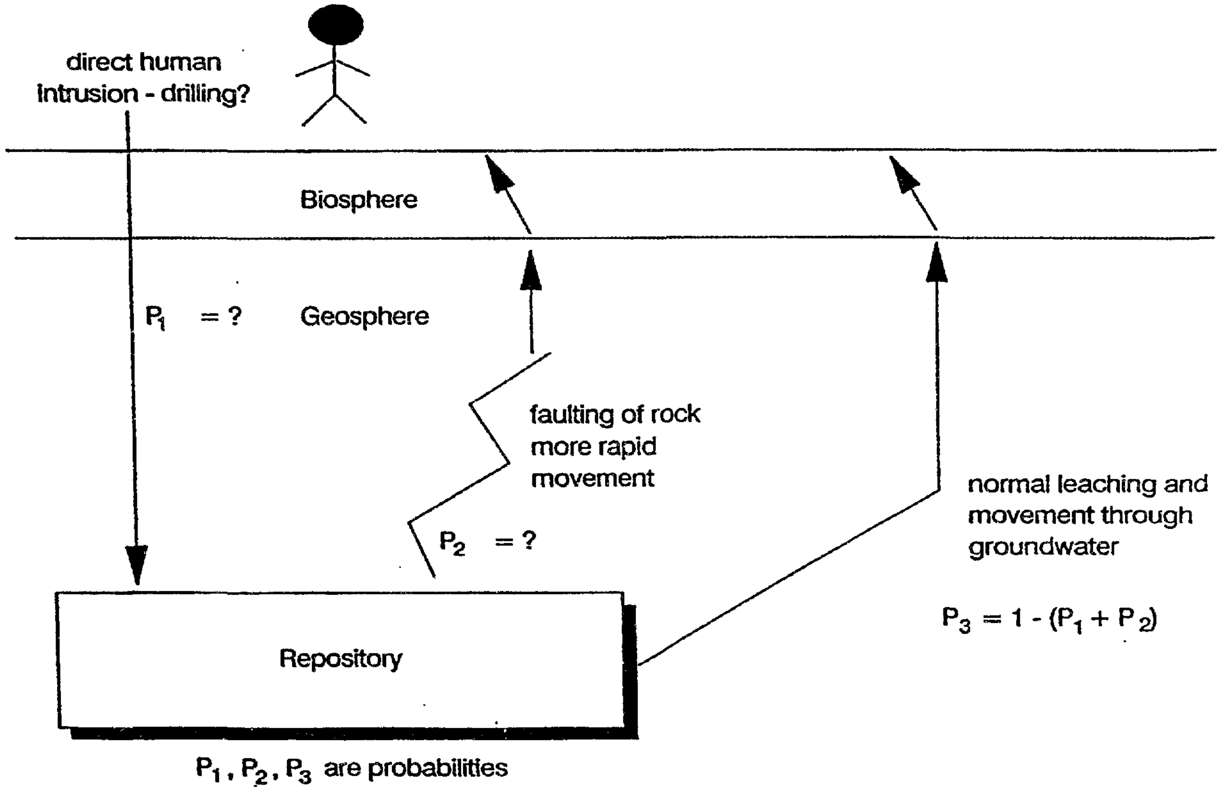

Figure A-1

A-3. POSSIBLE SOLUTIONS

There are, perhaps, two ways of overcoming the problem described above.

Firstly, waste could be diluted to such an extent that it is inconceivable that significant individual exposures could arise. To return to the example, suppose the exposure from examining a core of vitrified HLW at 100 years after closure is 12 Sv [A-1]; therefore, the waste would have to be diluted 12 000 times in order to reduce such exposures to 1 mSv, the ICRP dose limit for members of the public [A-2]. However, this would increase the cost of disposal enormously, involve many practical difficulties and almost certainly compromise the safety of the repository in other respects and without any significant reduction in collective dose. There are other factors which, no doubt, should be taken into account in the example, but it serves to illustrate the point that dilution does not solve the difficulty.

Secondly, radiological protection criteria could be framed in a way which acknowledge that significant exposures may occur but aim to limit their occurrence to acceptable levels. Exposure to ionising radiation may be harmful. At relatively high dose rates gross tissue damage may occur which usually leads to death: an instantaneous absorbed dose of about 5 Gy would probably be lethal. These so-called *deterministic effects* decrease in severity as the dose decreases and have a threshold dose below which they do not occur. Short term exposures below around 0.5 Sv will generally not give rise to deterministic effects. However, smaller exposures may also be harmful but in a different way. Exposure to ionising radiation increases the chance of contracting fatal cancer and the larger the dose of radiation, the greater is the chance. No dose of radiation is harmless but, conversely, only a few exposed people are likely to contract radiation-induced cancer. The situation is analogous to smoking where those who smoke most run the highest risk of lung cancer, but by no means all of them will contract it. ICRP refers to these effects of radiation where the likelihood of the effect increases with increasing dose as *stochastic effects*.

ICRP set the dose limit at a level where deterministic effects would not be experienced and stochastic effects would not be at unacceptable levels [A-2]. In order to assist in limiting stochastic effects, ICRP established a risk factor for exposure to low levels of ionising radiation. This risk factor is the likelihood, or probability, of incurring a radiation-induced fatal cancer per unit dose and has a value of $5\ 10^{-2}\ Sv^{-1}$. In other words if each individual in a population of all ages of, say, 10 000 people was exposed to a dose of ten milliSieverts, then on average five would die of radiation-induced cancer. On the basis of considering risk levels and the variation in natural background radiation, ICRP recommended a dose limit of 1 mSv a^{-1} for members of the public from all controlled sources.

From Equation (1), the dose limit could be seen as a limit on the chance of contracting a radiation-induced fatal cancer. Indeed, it is this chance that is important — if there were no chance of contracting cancer, then doses would not need to be limited to 1 mSv a^{-1}.

$$\textit{Dose} \times \textit{risk factor} = \textit{chance of contracting fatal cancer} \tag{1}$$

In this equation it is assumed that the individual will receive the dose. If it is not certain that the individual will receive the dose, then the chance of contracting a fatal radiation-induced cancer must be less. Therefore, the probability that the dose is received must be taken into account. The equation then becomes:

$$\textit{probability of receiving the dose} \times \textit{dose} \times \textit{risk factor} = \textit{chance of contracting fatal cancer} \tag{2}$$

For example, the chance of a fatal cancer in an exposed individual will be the same if 1 mSv is received (using Eq. (1)) as if there is a 50% chance of receiving 2 mSv (using Eq. (2)).

Thus, a limit on the chance of fatal cancer could achieve the purpose as the dose limit, but it could be applied consistently to a much wider range of situations.

To simplify the following discussions the term risk will be broadly defined as follows:

$$\textit{(probability of receiving an exposure)} \times \textit{(the probability that the exposure will give rise to a deleterious health effect)} \tag{3}$$

A.4. 'RISK' — THE ANSWER?

The application of the risk concept requires some further thought in that an individual in the future may be at risk, in more than one way, from the disposal facility. This is illustrated in Fig. A-1 which shows three possible, so-called, exposure scenarios: direct human intrusion, as discussed above; exposures arising from the gradual, normal leaching of the waste in the repository, referred to as the normal evolution scenario; and exposures arising if the host rock becomes faulted leading to a quicker rate of return to the biosphere.

From our present day perspective, an individual in the future could be considered to be at risk from more than one scenario; this can be taken into account in the following way. Each of these exposure scenarios should be assigned a probability with the sum of the probabilities being unity assuming they are the only scenarios considered necessary. In other words the scenarios should be mutually exclusive. The doses calculated to arise via each scenario should be multiplied by the assigned probability and then by the risk factor to produce a measure of risk. The calculated risks from each scenario could be summed in some way to produce a measure of the hazard to future individuals.

The summation across exposure scenarios may not be straightforward. The important point is that risks from different scenarios should only be summed where the same individuals could be at risk. For example, the most exposed individuals in the 'normal evolution' and the 'faulting' scenario might be, say, dairy farmers at a particular location who consume large quantities of milk and milk products from their herd which grazes on contaminated pasture. If there is no compelling reason why such dairy farmers should not exist at that location at that time in either scenario, then the risks from the two scenarios should be added.

However, there are cases where risks should not be added. For example, if the most exposed individuals for the human intrusion scenarios are technicians inspecting the heavily contaminated core, then the risk to these people should, perhaps, not be added to the risks to the dairy farmers in the 'normal' and 'faulting' scenarios.

The definition of 'risk', 'R', taking the points made above into account, becomes:

$$R = \gamma \sum_i P_i E_i \tag{4}$$

where γ is the risk factor (or probability) of the effect per unit dose, and P_i is the probability of scenario i which, if it occurs, gives rise to an effective dose E_i (assuming that this is less than about 0.5 Sv and that R refers to the same individual).

A particular problem in undertaking these risk calculations is the identification of an appropriate range of exposure scenarios and assigning probabilities to them. The set of scenarios should be adequate to encompass every reasonably plausible evolution of the site and therefore the sum of the scenario probabilities should be unity. Each scenario may represent a series of possible futures which have very similar radiological consequences and hence can be treated together as one possible future evolution.

It may require considerable effort to choose an adequate set of scenarios. Expert judgement, computer models of possible future conditions and natural analogues may assist in the process. Furthermore, our ability to distinguish between different scenarios may diminish as the time period being considered increases. Assigning probabilities to the scenarios is equally problematic and may appear a rather arbitrary process.

One point worth mentioning about these calculations is that individuals in the future are considered to be 'at risk' from more than one of the scenarios. However, at any point in time in the future, an individual will only inhabit one scenario. In the example (Fig. A-1) risks to the individual from the 'normal' and 'faulted' scenarios are summed but, clearly, from the future individuals viewpoint he will only be at risk from one or other of those scenarios — not both at the same time! It is worth noting that the risk actually experienced (the 'conditional' risk) could be higher or lower than the overall risk assessed from a present day perspective.

There is a variant on the risk calculations described above which avoids explicitly addressing scenario selection. In this methodology probabilistic risk assessment techniques are used to simulate the long term evolution of the natural environment relevant to the disposal site; and a measure of risk is obtained which is intended to take into account all possible futures

[A-3]. Essentially, models have been developed which represent possible future conditions of the site. A Monte Carlo simulation then generates samples of possible future evolutions covering periods of up to one million years into the future. The effect of these temporal changes and their associated uncertainties on estimates of the release from the repository, the environmental distribution of radionuclides and consequent risk are then evaluated.

A.5. PROBLEMS WITH 'RISK' — THE RETURN TO 'DOSE'

The preceding discussion of risk perhaps highlights the concept's Achilles heel — risk is a difficult idea to grasp; the more so for a member of the public who is concerned about the safety of a repository. Furthermore, people's perception of risk depends upon whether they can judge the hazard directly from experience or whether the cause of the danger is poorly understood. It may also be the case that people attach greatest significance to situations where there are particularly large adverse circumstances, even if the probability of occurrence is very small. (ICRP acknowledges in ICRP 46 [A-4] that "'risk' is used with different connotations in various disciplines".)

However, it is possible to have a risk criterion but express it in terms of a probability-weighted dose. In other words, a dose of 10 mSv having a probability of occurrence of 0.1 becomes a probability weighted dose of 1 mSv. The idea is attractive in that the resultant dose can be compared to a 'dose limit': a relationship which is easy to understand. However, this procedure has its limitations which mainly arise from the higher consequence, low probability events. One reason is that because of differences in the doses and dose rate, the risk factor may be different from the one normally applied to the dose limit. An extreme example is where deterministic effects may be important.

It is possible to express a 'risk' criterion in terms of doses and probabilities in a criterion curve. Figure A-2 shows a criterion curve for a risk constraint of 1 10^{-5} per year (fatal cancer and serious hereditary effects). The risk factor assumed is 6% Sv^{-1}. The risk constraint appears as a diagonal line representing the boundary between the acceptable and unacceptable regions. This curve shows that if the summed probability-weighted doses to a critical group from all the exposure scenarios are estimated to be less than about 200 μSv then the waste disposal site would satisfy the risk criterion *[1 10^{-5}/0.06 = 1.7 10^{-4} Sv]*. Furthermore, it can be seen that higher exposures can be accepted as long as their probability of occurrence is correspondingly lower. The dose range where deterministic effects become important is represented in such curves by a non-proportional region. In this example it is assumed that deterministic effects may be significant above exposures of 0.5 Sv and this is reflected in the vertical part of the curve (Fig. A-2). Deterministic effects could be taken into account by limiting their probability of occurrence (Fig. A-2). Such criterion curves may prove useful aids to presenting risk criteria in a graphical form.

A.6. THE HYBRID DOSE AND RISK CRITERIA

There are further ways of framing radiological protection criteria which deserve consideration. In Publication 46 [A-4], ICRP made their recommendations on radiological protection criteria for solid waste disposal. These recommendations embraced the concepts of both dose and risk limitation. The main points were as follows:

(i) the dose limit of 1 mSv a^{-1} for members of the public should be applied to situations in which normal, gradual processes lead to radionuclide releases from solid waste disposal sites;

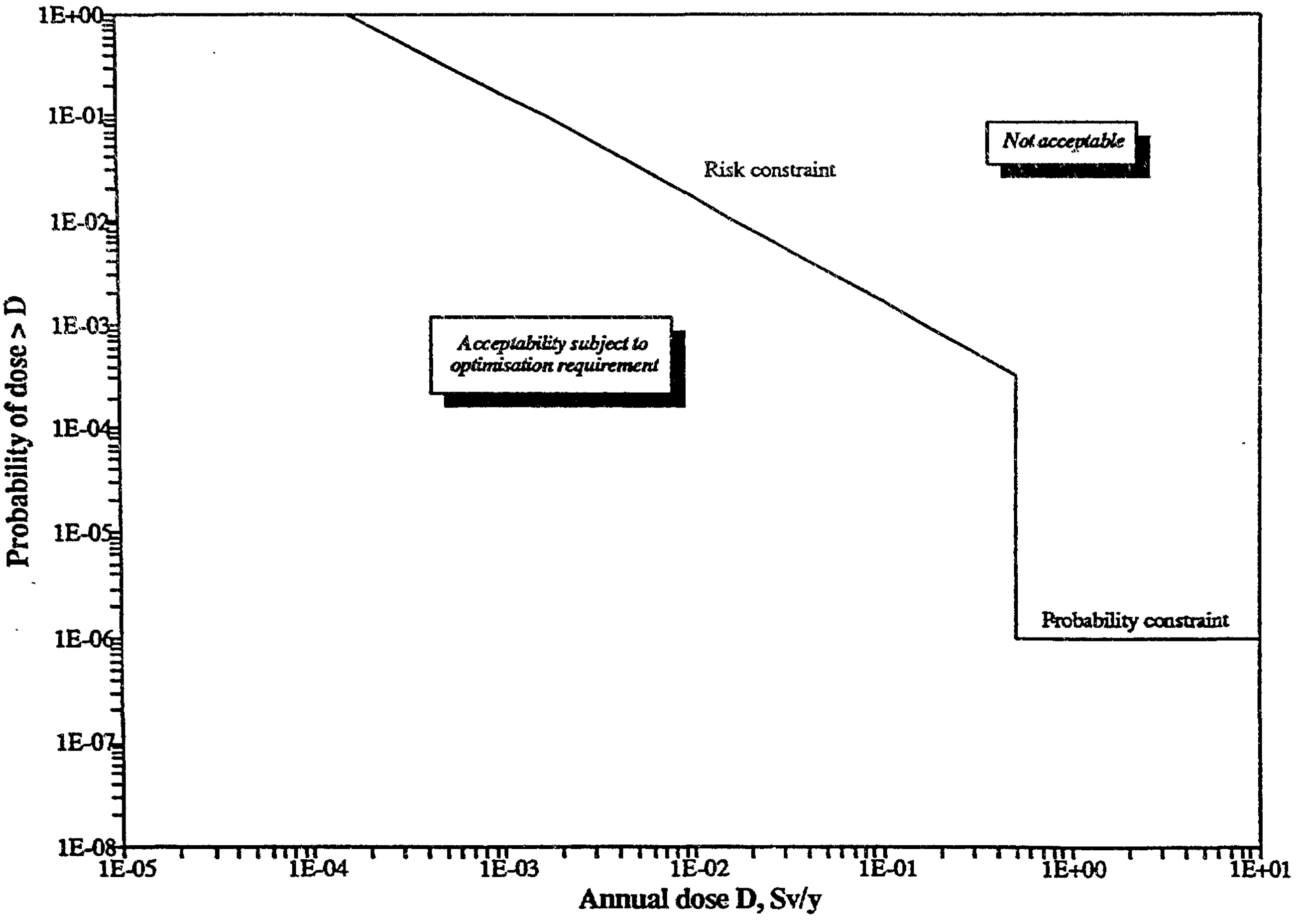

Figure A-2

(ii) a limit on individual risk of 10^{-5} a^{-1} should be applied for situations in which releases and doses are caused or influenced by probabilistic events and processes.

Several issues arise from these recommendations. Firstly, the inclusion of a dose limit may make the criteria easier for members of the public to understand. Secondly, the particular numerical values adopted by ICRP could be seen as problematic: the risk equivalent of a dose of 1 mSv, using the ICRP 26 risk factor [A-5], is approximately 10^{-5} and, therefore, the ICRP might appear to be allowing a risk to future individuals of 2×10^{-5}; however, the ICRP formulation does constrain the conditional risk experienced by an individual in the most likely scenario to be at or below the risk criterion (at least for cases such as ICRP 46 where the dose criterion corresponds to the risk criterion). A pure risk criterion does not necessarily do this.

ICRP's reasoning for having separate limitations for the 'normal' sequence of events and probabilistic events is that "the design and operational features that are intended to limit the two kinds of risk may be very different. Moreover, it is not self-evident that society would want to accept a small reduction in routine risks to compensate for an increase in the likelihood of an improbable, but serious, event".

The IAEA recommendations on "Safety Principles and Technical Criteria for the Underground Disposal or High Level Radioactive Wastes" [A-6] follow the ICRP approach of separate dose and risk limitation.

One further observation on hybrid criteria is that some countries have adopted dose limitation for the more likely radionuclide release scenarios but have expressed the criteria for other plausible scenarios in a qualitative way, i.e., the likelihood of doses above a specified limit should be sufficiently small. The rationale for such an approach is that it is impossible to obtain sufficiently accurate estimates of the probability for the more unlikely exposure scenario; a point which has been mentioned earlier and is worth considering.

A-7. CONCLUSIONS

1. To safely dispose of radioactive waste entails affording future individuals the same level of protection as individuals alive today and appropriate radiation protection criteria should be framed.

2. In order to adequately protect individuals in the future the possibility of exposures arising from events and processes having probabilities associated with them should be taken into account.

3. In general, three interrelated forms of radiological protection criteria are possible: dose limitation, risk limitation and a hybrid system combining dose limitation and risk limitation. The following conclusions can be drawn:

    (i) Criteria based solely on dose limitation are easy to understand but have their shortcomings if unlikely events have to be considered quantitatively.

    (ii) Risk based criteria are possibly conceptually the most satisfying but may have presentational difficulties.

    (iii) The hybrid dose/risk system overcomes many of the potential disadvantages of the two other methods but there are conceptual difficulties.

4. No matter what form of criteria are adopted there may still be problems in choosing 'futures' for the disposal facility and its environs, including the assumptions regarding human behaviour and assigning probabilities to events. This leads to one important topic which is not within this paper's remit — uncertainty. There is uncertainty surrounding virtually all aspects of long term assessments and it is essential that this uncertainty is dealt with as systematically and quantitatively as possible. Furthermore, issues arise as to how uncertainty is taken into account in judging compliance with any numerical criterion.

REFERENCES

[A-1] MOBBS, S.F., et al., Comparison of the Waste Management Aspects of Spent Fuel Disposal and Reprocessing: Post-disposal Radiological Impact, CEC, Luxembourg, EUR 13561 EN (1991).

[A-2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Ann. ICRP 21 (1-3), Pergamon Press, Oxford and New York (1991).

[A-3] LAURENS, J.-M., et al., "The development and application of an integrated radiological risk assessment procedure using time-dependent probabilistic risk analysis", Proc. NEA/IAEA/CEC Symposium on Safety Assessment of Radioactive Waste Repositories, OECD/NEA, Paris (1990).

[A-4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Principles for the Disposal of Solid Radioactive Waste, Publication 46, Ann. ICRP 15, No. 4, Pergamon Press, Oxford and New York (1985).

[A-5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication 26, Ann. ICRP 1, No. 3, Pergamon Press, Oxford and New York(1977).

[A-6] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, Safety Series No. 99, IAEA, Vienna (1989).

MEMBERS OF THE INWAC SUBGROUP ON PRINCIPLES AND CRITERIA FOR RADIOACTIVE WASTE DISPOSAL AND CONSULTANTS

Abe, M. (2)	Department of Decommissioning and Waste Management, Tokai Research Establishment, JAERI, 2-4, Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan
Barescut, J.-C. (4)	CEA/IPSN/DPEI, B. P. No. 6, F-92265 Fontenay-aux-Roses, France
Bell, M. (2)	International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Blanc, P.-L. (1)	CEA/IPSN/DPEI, B. P. No. 6, F-92265 Fontenay-aux-Roses, France
Bragg, K. *(Chairman)* (2, 3, 4)	Atomic Energy Control Board, P.O. Box 1046, Station B, 270 Albert St., Ottawa, K1P 5S9, Canada
Carboneras, P. (2, 4)	Empresa Nacional de Residuos Radioactivos SA, Emilio Vargas 7, E-28043 Madrid, Spain
Chapuis, A.M. (2)	CEA/IPSN/DPEI, B. P. No. 6, F-92265 Fontenay-aux-Roses, France
Cooper, J. (2, 3, 4)	National Radiological Protection Board, Chilton, Didcot, Oxon OX11 ORQ, United Kingdom
Galpin, F. (2)	Office of Radiation Programs, US Environmental Protection Agency, 401 M. Street, S.W., Washington, DC 20460, United States of America
Gera, F. (2)	ISMES Spa, Via dei Crociferi, 44, I-00187 Rome, Italy
Gonen, Y. (2)	Israel Atomic Energy Commission, 26, Rehov Chaim Levanon, P.O. Box 7061, IL-60170 Tel-Aviv, Israel

Isagawa, H. (2)	Radioactive Waste Management Project, Power Reactor and Nuclear Fuel Development Corporation, 9-13, 1-Chome, Akasaka, Minato-ku, Tokyo 107, Japan
Inoue, H. (4)	Office of Radioactive Waste Regulation, Nuclear Safety Bureau, Science and Technology Agency, 2-1, Kasumigaseki 2-Chome, Chiyoda-ku, Tokyo 100, Japan
Koch, L. (4)	European Institute for Transuranium Elements, Commission of the European Communities, P. O. Box 2340, D-76125 Karlsruhe, Germany
Kocher, D. (2, 4)	Health Sciences Research Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6383, United States of America
Linsley, G. *(Scientific Secretary)* (1, 2, 3, 4)	International Atomic Energy Agency, P. O. Box 100, A-1400 Vienna, Austria
Matsushita, T. (2)	Office of Radioactive Waste Regulation, Nuclear Safety Bureau, Science and Technology Agency of Japan, 2-2-1 Kasumigaseki, Chiyoda-ku, Tokyo 100, Japan
McCombie, C. (2, 4)	National Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA), Hardstrasse 73, CH-5430 Wettingen, Switzerland
Nagamatsuya, T. (4)	Office of Internal Affairs, Japan Atomic Energy Research Institute - Vienna Office, Baumannstrasse 4/2/13, A-1030 Vienna, Austria
Naim, E. (4)	Radiation and Safety Department, Nuclear Research Centre - Negev, Israel Atomic Energy Commission, P.O. Box 9001, Beer-Sheva 84190, Israel
Norrby, S. (2, 4)	Swedish Nuclear Power Inspectorate, Box 27106, S-102 52 Stockholm, Sweden

Olivier, J-P. (2, 4)	OECD/Nuclear Energy Agency, Le Seine-Saint-Germain, 12 Boulevard des Iles, F-92130 Issy-les-Moulineaux, France
Röthemeyer, H. (1, 2, 3, 4)	Bundesamt für Strahlenschutz, Bundesallee 100, D-3300 Braunschweig, Germany
Ruokola, E. (2, 4)	Finnish Centre for Radiation and Nuclear Safety, P.O. Box 268, SF-00101 Helsinki, Finland
Schaller, K. (2, 4)	Commission of the European Communities, DG XI, Office BU-5 6/179, 200 rue de la Loi, B-1049 Brussels, Belgium
Smith, R. (2, 4)	Her Majesty's Inspectorate of Pollution, Romney House, 43 Marsham St., London SW1P 3PY, United Kingdom
Snihs, J.-O. (1, 2, 3, 4)	Swedish Radiation Protection Institute, Box 60204, S-104 01 Stockholm, Sweden
Warnecke, E. (2, 4)	International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
Zurkinden, A. (2, 4)	Section for Radioactive Waste Management, Swiss Nuclear Safety Inspectorate, CH-5232 Villigen-HSK, Switzerland

Consultants Meeting, 1–5 June 1992 **(1)**

Meetings of the INWAC Subgroup
27–29 October 1992 **(2)** and 19–21 October 1993 **(4)**

Consultants Meeting, 24–28 May 1993 **(3)**